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EVALUATION OF SEA ICE THICKNESS SENSORS

Prepared for
Transportation Development Centre
Transport Canada

by

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Final Report

March 1988

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Un sommaire en français de ce rapport est inclus avant la table des matières.

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17. Abstract

As operations in Canadian ice-infested waters increase, so will the need for an effective helicopter-borne ice thickness sensor. This study evaluated three experimental systems: C-CORE impulse radar, MPB synthetic pulse radar, and Geotech electromagnetic (EM) induction system, near Resolute Bay, N.W.T., in April-May 1987, over first-year and multi-year sea ice and iceberg fragments. Measurements were made from a Bell 206L helicopter at altitudes of approximately 30 m and speeds up to 100 knots. The synthetic pulse radar was not operational on arrival in the Arctic. The impulse radar performed as expected over cold, undeformed, relatively non-saline ice to give ice thickness to ± 20 cm or better. As ice salinity or deformation increases, ice bottom echoes become very weak. The prototype EM induction system gave ice thickness ± 50 cm or better; improved results would be expected from an updated version.

It is recommended that development of an operational EM system to measure ice thickness be considered. It is expected that an EM system would meet or exceed most of the helicopter ice thickness sensor target specifications for most ice types. A system could be built in Canada over three years at a cost of about $1 million, including field testing.

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17. Résumé

À mesure que la navigation maritime s'intensifie dans les eaux canadiennes chargées de glace, le besoin d'un appareil fiable de télémesure de l'épaisseur des glaces de mer à partir d'un hélicoptère se fait plus pressant. Ce rapport traite de l'évaluation de trois systèmes expérimentaux près de Resolute Bay (T.N.-O.) en avril-mai 1987: le radar à impulsions C-CORE, le radar à impulsions synthétiques étudié par MPB et un système à induction électromagnétique conçu par Geotech. Les expériences ont concerné des glaces de mer de première et de plusieurs années ainsi que des fragments d'iceberg. Elles ont été faites à partir d'un hélicoptère Bell 206L volant à environ 30 mètres d'altitude à des vitesses allant jusqu'à 100 noeuds. Le radar à impulsions synthétiques ne fonctionnait pas à son arrivée dans l'Arctique tandis que le radar à impulsions a affiché les performances prévues en présence de glace froide, intacte et à salinité très faible, atteignant un degré de précision de ± 20 cm ou mieux. A mesure que la salinité ou la déformation de la couche de glace s'accentue, les signaux réfléchis par le fond de la couche de glace deviennent de plus en plus faibles. Le système à induction électromagnétique expérimental a affiché une marge d'erreur de ± 50 cm ou mieux, mais on pense qu'une version réétudiée donnerait de meilleurs résultats.

Il est recommandé d'envisager la mise au point d'un système à induction électromagnétique opérationnel, étant donné qu'un tel système devrait pouvoir atteindre ou même dépasser la plupart des performances exigées d'un système de télémesure à partir d'un hélicoptère et ce, dans la plupart des types de glace. On pense qu'un tel système pourrait être réalisé au Canada en trois ans, à un coût d'environ un million de dollars, essais in situ compris.

18. Mots-clés	19. Diffusion
Epaisseur des glaces, glace de mer, Arctique, induction électromagnétique, hélicoptère, capteurs, radar à impulsions, radar à impulsions synthétiques, radar à ouverture synthétique	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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The electromagnetic induction work was carried out by a team from Geotech Limited led by Nick Valleau and Scott Holladay. Their efforts were a major contribution to this study. We thank Hector Olivera and Carl Kirkpatrick for their work in the field.

The field work was facilitated by a number of people and organizations. Polar Continental Shelf Project Resolute Base provided logistic support, accommodation and on-site transportation facilities. We thank Barry Hough and his staff for their 'can do' attitude. The good humour and valuable assistance of the Okanagan Helicopter staff - Jim Scott, engineer, and Gord Southern and Dave White, pilots - were instrumental to the success of the airborne measurements.

Radar imagery of the area was kindly provided by Canarctic Shipping Company Limited (STAR-1 and STAR-2) and by Atmospheric Environment Service Branch (Motorola SLAR). Parts of the electromagnetic system were borrowed from the Canadian Hydrographic Service. Snow thickness data were provided by Dr. Alex Herman of the Bedford Institute of Oceanography. Ice measurement equipment was provided by the Centre for Cold Ocean Resources Engineering. Interpretation of the SAR data was provided by Dr. Ray Lowry, Intera Technologies Ltd.

SUMMARY

As operations in Canadian ice-infested waters increase, particularly with commissioning of the Polar-8 icebreaker, there will be a need for an effective helicopter-borne ice thickness sensor. Such a device could provide tactical ice information for an icebreaker and would complement ice imagery data.

No operational sensor is currently available. In this study three experimental systems were examined: C-CORE impulse radar, MPB synthetic pulse radar, and Geotech electromagnetic (EM) induction system. The field tests were conducted near Resolute Bay, N.W.T., in April-May 1987, over first-year and multi-year sea ice and iceberg fragments. Measurements were made from a Bell 206L helicopter at altitudes of approximately 30 m and speeds up to 100 knots.

The synthetic pulse radar was not operational on arrival in the Arctic. The impulse radar performed as expected over cold, undeformed, relatively non-saline ice - when echoes are received they can be interpreted to give ice thickness to ± 20 cm or better. As ice salinity or deformation increases, ice bottom echoes become very weak. The EM induction system is relatively new for this application. The prototype used here gave ice thickness ± 50 cm or better, and improved results would be expected from an updated version based on this experience.

Because EM induction systems are expected to perform well over a wide variety of ice types, it is recommended that an operational EM system to measure ice thickness be developed. The technology is relatively mature, and it is expected that an operational system would meet or exceed most of the helicopter ice thickness sensor target specifications set by TDC. A system could be built in Canada over three years at a cost of about $1 million, including field testing.

SOMMAIRE

A mesure que la navigation maritime s'intensifie dans les eaux canadiennes chargées de glace, particulièrement avec la mise en service des brise-glaces de classe Polar-8, le besoin d'un appareil fiable de télémesure de l'épaisseur des glaces de mer à partir d'un hélicoptère se fait plus pressant. Un tel appareil servirait à fournir aux brise-glaces une information tactique à court terme sur les conditions glacielles, en complément de l'imagerie radar disponible.

A l'heure actuelle, il n'existe aucun appareil de cette nature qui soit opérationnel. Ce rapport concerne l'expérimentation de trois systèmes expérimentaux, soit le radar à impulsions C-CORE, le radar à impulsions synthétiques MPB et un système à induction électromagnétique conçu par Geotech. Les essais en mer ont eu lieu près de Resolute Bay (T.N.-O.) en avril-mai 1987; ils ont concerné des glaces de première et de plusieurs années, ainsi que des fragments d'iceberg. Les expériences ont été faites à partir d'un hélicoptère Bell 206L volant à une altitude d'environ 30 mètres, à des vitesses atteignant 100 noeuds.

Le radar à impulsions synthétiques n'était pas opérationnel à son arrivée dans l'Arctique. Quant au radar à impulsions, il a affiché les performances attendues en présence de glaces froides, non déformées et à salinité très faible: les échos reçus permettent d'estimer l'épaisseur de la glace à $\pm$ 20 cm près ou mieux. A mesure que la salinité ou la déformation de la glace s'accentue, les signaux réfléchis par le fond de la couche de glace deviennent très faibles. L'idée d'utiliser un système à induction électromagnétique est relativement nouvelle dans ce domaine. Le prototype utilisé a affiché une marge d'erreur de $\pm$ 50 cm ou mieux, mais on pense qu'une version améliorée aurait donné de meilleurs résultats.

Etant donné que les systèmes à induction électromagnétique devraient donner de bons résultats dans une gamme étendue de types de glace, il est recommandé de lancer la mise au point d'un système opérationnel. Cette technologie est arrivée à un point de développement relativement poussé et on peut s'attendre qu'un système opérationnel atteigne ou même dépasse la plupart des exigences formulées par le CDT en ce qui concerne les performances d'un appareil de télémesure de l'épaisseur des glaces à partir d'un hélicoptère. Un tel système pourrait être construit au Canada en trois ans, à un coût d'environ un million de dollars, essais in situ compris.

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1. INTRODUCTION

Measurement of the thickness of the many types of floating ice, particularly for rapid surveys over large areas, poses an important problem in development of Canada's marine resources. The enormous range of ice types, in the various regions, over all seasons, places constraints on shipping, drilling, fishing and offshore construction. In addition, ice thickness is an important parameter in many scientific studies, such as ice and climate modelling [1*].

In April 1986, Canpolar Inc. was contracted by the Transportation Development Centre (TDC) of Transport Canada to evaluate several sensors for measuring sea ice thickness from a helicopter.

The objectives of the study were:

1. To evaluate, under field conditions, the types of equipment available in Canada to measure sea ice thickness from a helicopter, and assess the effectiveness of each sensor.

2. To make recommendations for improving individual systems and/or developing an improved ice thickness measurement capability.

The sensors investigated were an electromagnetic (EM) induction system developed by Geotech Limited of Markham, the C-CORE impulse radar system, and a Synthetic Pulse Radar (SPR) system designed and built by MPB Technologies Inc. of Dorval for the TDC. In addition, Synthetic Aperture Radar (SAR) data of the field site were available. Field evaluations were conducted near Resolute Bay, N.W.T. in April - May, 1987.

This report describes the equipment used, summarizes the field program and data interpretation, and comments on the results in terms of future directions.

* Numbers in square brackets designate references listed at the end of the report.

2. EQUIPMENT AND TECHNOLOGIES

Several different systems were considered for inclusion in this study. These systems encompassed two main technologies - short pulse radars operating in the VHF frequency band, and an electromagnetic induction system. Several radar systems for ice thickness measurement have been developed over the past decade, including:

- C-CORE impulse radar system, specifically designed for airborne ice thickness measurement;
- MPB synthetic pulse radar system developed for Transport Canada;
- Step-frequency radar developed at the University of Toronto;
- Impulse radar system developed by Cambridge Consultants Limited, U.K. for Exxon Corporation;
- GSSI impulse radar systems used successfully by several researchers at the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A.

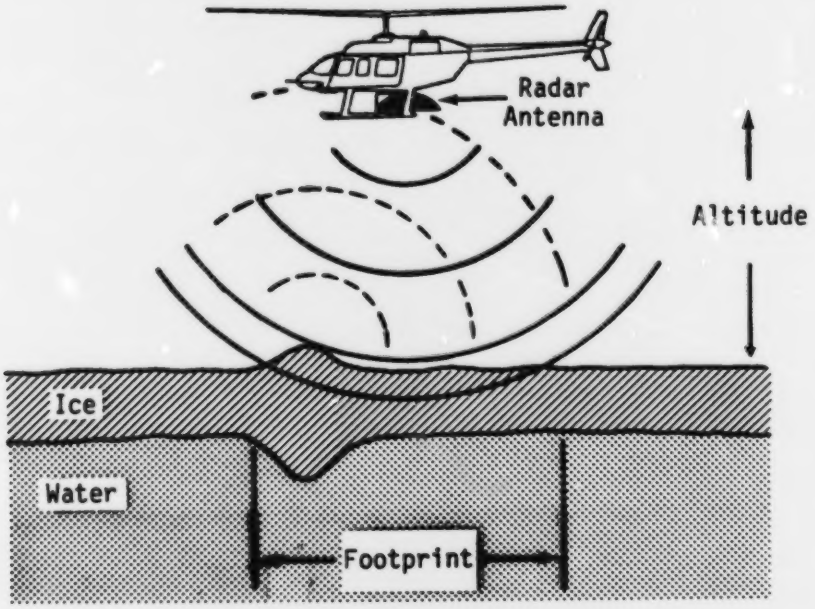
For reasons of availability and logistics only the first two systems were ultimately available to this study. The only electromagnetic system designed specifically for ice thickness measurement was one under development at Geotech Limited, Markham, and the first prototype system was included in this study.

The radar systems transmit VHF pulses (around 100 MHz) which can penetrate many types of ice. The delay time between the echoes from the ice surface and the ice bottom is indicative of the ice thickness (Figure 1). The main limitation to this type of system is that many important ice types, such as ridges, are opaque to the radar signals.

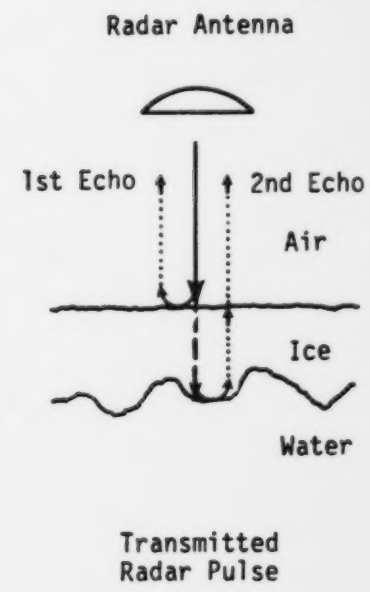
EM indication uses much lower frequencies - around 500 to 50,000 Hz - which are not significantly affected by ice. An EM field is set up in the underlying water by the transmitted primary field (Figure 2). A secondary EM field is detected by the receiver and interpreted to give the sensor's distance from the water. A laser profilometer gives the distance to the top of the snow-ice layer, and the difference is the snow plus ice thickness.

Although not specifically an ice thickness sensor, data from a Synthetic Aperture Radar (SAR) were also available to this study. This sensor provides high resolution areal imagery of the ice and imaging radar data are becoming readily available to arctic operations. Therefore, it was of interest to determine how this type of data would be complemented by ice thickness data.

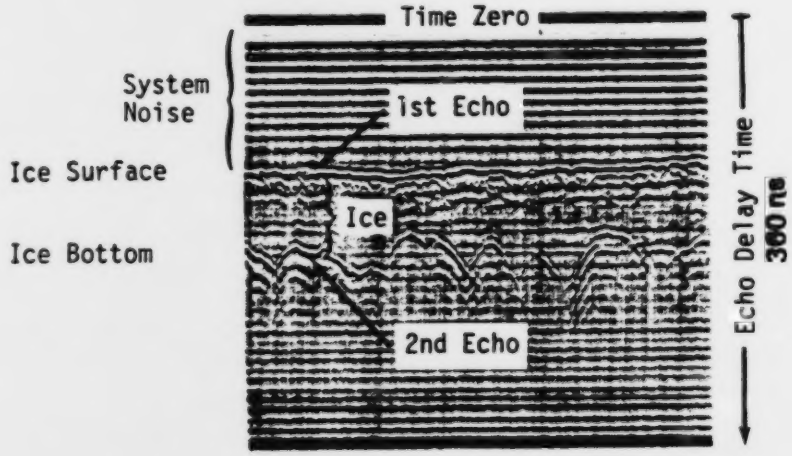
In this chapter the various technologies used are described.



a) Geometry of airborne impulse radar.
Note : Altitude ~ Footprint.



b) Radar sounding principle of operation.



c) Sample impulse radar analog recording of a multi-year sea ice profile. Note uniform horizontal lines are part of system noise.

Figure 1. Principle of operation of a helicopter-borne impulse radar ice thickness sensing system.

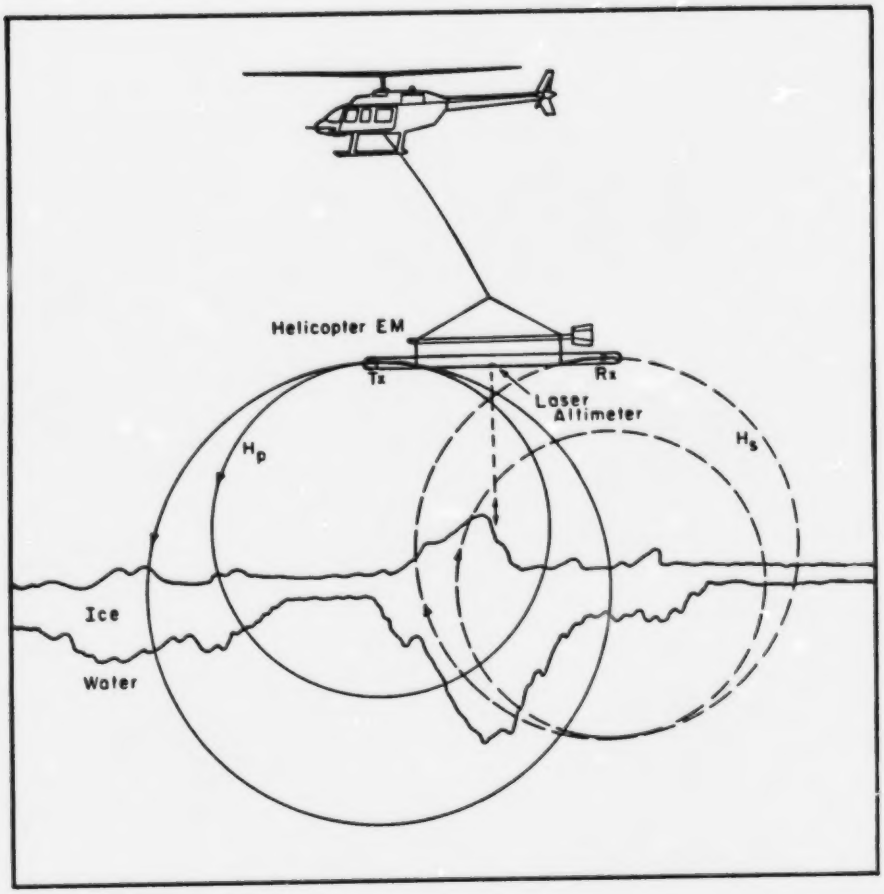


Figure 2. Illustration of helicopter-borne EM induction sensing system. The transmit coil creates a primary magnetic field H_p which sets up eddy currents in a conductive medium such as Ice. A secondary magnetic field H_s thus results which is detected by the receive coil. [from Kovacs et al., 1987].

2.1 C-CORE Impulse Radar System

The impulse radar system used was developed at the Centre for Cold Oceans Resources Engineering (C-CORE), Memorial University of Newfoundland, from 1976 to 1980, specifically for measuring ice thickness from a helicopter. Its specifications are given in Table 1. Overall description of this system and comparison to other impulse radar systems are given by Butt and Gamberg [2].

The impulse radar antenna transmits a broad-band electromagnetic pulse with a centre frequency largely determined by antenna size. Shaping of the pulse is accomplished by the three-dimensional shape of the antenna and by resistive loads placed in the antenna. A fairly clean monopulse or triplet can be achieved with relative bandwidths of approximately 100 percent. The 120 MHz centre-frequency was chosen as a trade-off between resolution and attenuation. Attenuation increases rapidly with increasing frequency in sea ice [1]. At its centre frequency the wavelength emitted by this antenna is 2.5 m; in ice, this wave length us approximately 1.2 m. The antenna transmits a "triplet" (three half-cycles) of 12 ns duration and is backed by a hyperbolic reflector so that the presence of the helicopter does not appreciably alter the pulse shape.

The system operates similarly to a sampling oscilloscope to reduce the high speed radar signals, transmitted at a pulse repetition frequency of 51.2 kHz, to an audio frequency data stream with an effective pulse repetition rate of 64 scans per second. These data are recorded on the high fidelity audio channels of a portable video cassette recorder. The system is also equipped with a Background Noise Removal System (BGNR) which reduces systematic ringing in the system by up to about 20 dB, by subtracting the signal received when the aircraft is flying well above the surface.

The diameter of the illuminated footprint of the radar is approximately the flying height, since the radiated pattern is basically that of a dipole antenna (Figure 1a). Since the first arrival travels the most direct path, it is normally from directly beneath the aircraft. For undeformed ice of moderate salinity both the ice surface and bottom echoes are received.

However, echoes can also be received from off to the side. These features act as point targets and present hyperbolic echoes as the radar passes them. In this case the shape of the echo on the record is not the actual shape of the reflector, but a function of the target-radar geometry. In addition, rough surfaces randomly scatter the incident pulse, thus reducing the amplitude of both the reflected echo and the amount of energy transmitted into the next layer.

Table 1. Specifications of C-CORE Impulse Radar System

Centre Frequency:	120 MHz
Approx. Bandwidth:	60 to 180 MHz
Approx. Pulse Length:	12 ns
Antenna Size:	148 cm x 120 cm x 36 cm
Antenna Configuration:	Monostatic shielded transceiver
Antenna Mount:	Hook deployed frame for Bell 206B or 206L
Approx. Peak Power:	50 watts into 200 ohm load
Approx. Performance Figure:	115 dB (includes receiver gain)
Scan Rate:	64 scans/second
Range Window:	90 or 360 ns (switch selectable)
Window Offset:	0', 50', 100', 200'(switch selectable)
Real-time display:	A-scope CRT (5.0 x 3.5 cm)
Dynamic Range:	66 dB for +3 dB S/N
Max. Signal Gain after Receiver:	46 dB (excluding time gain)
Max. Time Gain after Receiver:	24 dB
Background Noise Removal:	Up to 20 dB effective improvement
Recording:	JVC Hi-Fi VCR 2 FM audio channels for data -frequency response 20 Hz to 20 kHz -80 dB dynamic range -1 video channel for flight path imagery
Power Requirements:	Control module - 100 watts at 28+2 VDC
Physical Dimensions:	Control module - 58.5 x 35.0 x 34.0 cm
Weight:	Control module - 19 kg Antenna and frame - 50 kg

The system was flown 15 to 50 m above the ice at a speed of 30 to 75 knots. The results were recorded on magnetic tape and played back to visicorder grey-level strip chart recorder (Figure 1c). The analog data were later digitized and top and bottom echoes picked manually. In addition to the impulse radar data, a downward-looking video camera mounted in the helicopter provided imagery of the ice. These data were recorded on the video channel of the video cassette recorder and used to verify aircraft position along lines that were marked on the ice surface.

2.2 MPB Synthetic Pulse Radar System

MPB Technologies of Dorval, Quebec, have been working on development of a helicopter sea ice thickness radar system for several years under contract to the Transport Canada Research and Development Centre (TDC), Montreal. Their work is summarized in a series of reports [3, 4]. MPB worked on three different approaches to ice thickness measurement using VHF radio frequencies: (1) synthetic pulse radar (SPR) using frequencies of 30, 60, 90, 120 and 150 MHz; (2) amplitude modulated radar (AMR) using a relatively narrow band at 90 or 100 MHz; (3) video pulse radar (VPR) using a 5 ns pulse-width impulse radar.

The synthetic pulse system generates its pulse electronically, rather than in the antenna, by synthesizing five Fourier harmonics from 30 to 150 MHz. A controlled pulse shape can be obtained by adjusting the amplitude and phase of each of the components. Transmit and receive functions for either the SPR or AMR set of electronics are run through the same antenna, depending on the ice thickness expected (operator selectable).

The system uses a sampling technique similar to other impulse radars to reduce the radio frequency signal to audio frequencies. The audio signals are controlled by a built-in microprocessor for processing, recording and display functions.

The initial prototypes of the SPR and AMR were tested in 1980 in the Arctic by MPB [5]. Subsequently, a number of modifications were made and the VPR was tested in 1983 on Lake Melville. In 1985 Canpolar examined the VPR and noted that the SPR had been disassembled. This system was reassembled for bench tests in March 1987 [6].

For these bench tests the wideband transmitter of the VPR was used in conjunction with the five narrow passbands of the SPR receiver. The unit appeared to meet its functional specifications. When Canpolar shipped the unit to Toronto and then to the Arctic, a number of operational problems were encountered, including arcing, intermittent operation, and unsuitable connectors. In spite of these difficulties the unit was taken to the Arctic, but when it arrived it was no longer functional.

The antenna designed for the MPB sensor is a loaded dipole with shielding that can be quickly mounted and disconnected from a Bell 206B helicopter. Although some of the welds failed during shipment, this approach appears mechanically effective and easy to operate. Because of the necessity to

rebuild the MPB unit before any further testing could take place, and because it is not yet clear that the synthetic pulse radar is more effective in principle than existing impulse radars, and because of the inherent limitations of radar sounding of sea ice, further development work is not recommended.

2.3 Geotech EM System

The equipment used for this aspect of the field work consisted of a prototype airborne EM system, a laser altimeter, a video flight path recover system and a digital data acquisition system (DAS). This technology has been discussed in several publications [7, 8]. A general description of the integrated system and including unusual features of the prototype system are documented here.

2.3.1 System Components

The fixed-frequency airborne EM system was comprised of two major components: a sensor platform or "bird" towed beneath the aircraft and a receiver console located within the aircraft. The bird houses a set of transmitting and receiving coil systems, one for each frequency, and also carries ancillary equipment such as a laser altimeter and pitch and roll sensors. The bird shell is an essential part of the sensor, since it provides the dimensional stability required for precise separation of the primary or transmitted field from the secondary or induced field: the secondary field amounts to a reflection of the transmitted energy by nearby conductive zones, such as the sea water surface, and is essentially absent when the system is flown at high altitude.

Precise measurement of the secondary field is the objective in any EM application. This is rendered difficult by the strength of the primary field relative to that of the secondary field: an effective dynamic range of 140 dB is desirable for such measurements. In order to reduce this enormous dynamic range, "bucking" coils are included in the receiver coil circuits. These coils are designed and located in such a way that their output voltage cancels virtually all of the receiver coils' output voltage due to the primary field component. Measurement of changes in the secondary field strength due to motion of the system relative to nearby conductors then requires much less dynamic range in the receiver console.

A standard bird ranges from 6 to 8 metres long, with a diameter of 50 cm and weighs about 300 kg. It is normally flown 30 m above the surface and 30 m below the helicopter.

The receiver amplifies, filters and processes the signal from the receiver coils. This processing consists of analysis of the sinusoidal received voltage with respect to the phase of the transmitted signal: its outputs are representative of received signal strength in-phase and out-of-phase with the transmitted field.

Estimation of ice thickness using EM requires a precise estimate of the distance between the bird and the top of the ice. This estimate is provided by an Optech Model 60 laser altimeter mounted in the bird; a downward-looking window is provided for the laser beam in the bird shell. Since the bird altitude strongly affects both the EM and laser altimeter measurement, pitch and roll sensors are also mounted in the bird to monitor bird altitude. Signals from all sensors in the bird are sent to the receiver console and data acquisition system through a multiple-conductor cable.

A radar altimeter is normally installed for helicopter surveys. Its function is to provide the pilot with a consistent indication of helicopter altitude, both for safety purposes and to help maintain the bird at the desired survey altitude. The radar altitude is also useful as a consistency check or to fill in gaps in the laser altimeter record.

A lightweight video flight path recover system was also installed in the helicopter. This system consists of a JVC colour video camera with a sensing element, an 8 mm videotape recorder and a video annotation module which interfaces to the system. The camera was mounted inside the helicopter looking down, while the VCR was located near the main equipment for ease of operator access.

The data acquisition system used for this work was on RMS DGR33 rented from the manufacturer. This unit acquired analog and digital data from all sensors at a rate of ten samples per second, printed them on paper charts, and stored them on magnetic tape. It also provided a consistent timebase for data acquisition, generating "fiducial numbers" which were stored and printed with the data and added to the video flight path information being recorded by the VCR. This information permits the interpreter or data analyst to locate corresponding data points on the chart, digital, and video records of the survey.

One feature of this data acquisition system is that it can accommodate a dynamic range of 16 bits (96 dB) in the analog channels. This is particularly useful for airborne ice measurement since large anomalies are encountered when the bird altitude drops below 25 m. If the data acquisition system were to saturate every time the altitude hit this level, a significant amount of data would be lost. Integration of these instruments was relatively straightforward since analog outputs were used in all cases and sent to the analog input module of the DGR33 for digitization.

2.3.2 The Prototype Bird

The prototype EM bird utilizes a coil separation of 4 m, compared to the 6.5 m coil separation of a standard Geotech EMEX-I bird. It incorporated other design changes as well, such as the use of a small-diameter (30 cm) shell, a new suspension, and concentric 4500 and 32 kHz coil pairs. Because the coil separation is only 0.62 that of a standard bird, the anomalies over a given set of conditions will be reduced by the cube of 0.62 = 0.24, or roughly four times.

Consequently, noise and drift would have to be reduced four times over the "standard" levels to give comparable performance. In fact, this level of performance was not achieved in the prototype bird, although subsequent work indicates that there are no fundamental problems in designing stable, low-noise, short birds. The key advantages of the short bird are that it is easier to deploy and to ship than standard birds. This advantage is most important when it is necessary to ship the bird by air, as is normally required in the Arctic. Standard birds require multiple pallet spaces in a large cargo bay, whereas this bird can be loaded into the smaller bays normally available on passenger aircraft.

The small bird diameter turned out to be relatively undesirable, because it reduces the available room for transmitting coils substantially. An increment of 5 cm in diameter produced significant improvements in the characteristics, of the low-frequency transmitting coil. The suspension of this bird also departed from the usual Geotech pattern. Instead of using two pairs of yokes inside the bird, the bungee was passed around the outside of the spreader bar and the bird. It was secured by means of bolts running through a fiberglass flange molded onto the bungee cord. While this suspension reduced breaking stresses on the bungee, it had the unfortunate effect of increasing bird roll somewhat. This effect is not particularly troublesome.

2.4 SAR System

An effective remote sensing technique of surveying ice infested waters is by means of airborne Synthetic Aperture Radar (SAR). Prior research has demonstrated the capabilities of SAR imagery to discriminate various types of sea ice [9, 10, 11]. These studies have shown that fine resolution SAR imagery is of great utility as an ice reconnaissance tool.

Intera STAR-1 and STAR-2 SAR operational parameters are shown in Table 2. The radar is flown at a nominal altitude of 10.1 km to provide wide swath coverage and high fuel efficiency. An image is produced in real time by a digital image formation processing system aboard the aircraft. The SAR image is also recorded on 14-track High Density Digital Tape. Depending on requirements, digital radar data (recorded on the aircraft) may be down-linked as imagery in real-time mode, and/or produced as hardcopy or digital products in ground stations.

Table 2. Intera SAR Operational Parameters

Operating Altitude	10.1 km
Wavelength	X-Band
Polarization	Horizontal
Viewing Direction	Right or left 90^{0} from Ground Track
Maximum Aircraft Ground Speed	180 m/s (360 Knots)
Multi-Looks (azimuth)	1 to 7

Coverage and Resolution:

	STAR-1		STAR-2	
	High Res.	Wide Swath	High Res.	Wide Swath
Ground Swath Width (km)	23	46	17	63
Range Resolution (m)	6	12	5	18
Azimuth Resolution (m)	6	6	8	8

3. FIELD PROCEDURES

Personnel and equipment were mobilized at Polar Continental Shelf Project (PCSP) Base Camp, Resolute, N.W.T. on April 24, 1987. A detailed description of the activities performed during the field campaign can be found in a previous field report [12] and are not discussed here.

3.1 Project Site

The field work portion of this project was carried out in the vicinity of Resolute, N.W.T. on Cornwallis Island in Canada's Arctic Archipelago (Figure 3). This site was selected because of the availability of logistic support from PCSP and the likelihood of encountering both first-year and multi-year ice.

Intera STAR-2 SAR imagery of February 15, 1987, collected for Canarctic Shipping Company Limited, was used to preview the status of the sea ice prior to mobilization of equipment and personnel to base camp. Based on visual assessment of this SAR imagery, ice in the study area was found to be predominately level, uniform first-year ice extending for many miles around Resolute. Also, several multi-year floes were identified near Lowther Island, about 70 km west of Resolute. Based upon this preliminary assessment, three major survey lines, designated Lines 1, 2 and 3, were established over the ice infested waters of Barrow Strait and Resolute Passage (Figures 4 and 5). Lines 1 and 2 covered near shore first-year ice consisting of several iceberg fragments, and exhibiting an apparent discontinuity in the first-year ice sheet evident in the SAR imagery of Allen Bay (Figure 6). Line 3 traversed a multi-year ice floe consisting of a small first-year ice pressure ridge situated several kilometers north east of Lowther Island (Figure 7).

3.2 Activities

Activities included setting up the survey lines, measuring ice and snow thickness directly, overflying with the impulse radar and EM sensors, and playing back data for verification. Salinity measurements were made on collected samples in the base camp. Weather over the period was generally fair, with temperature ranging from $-10^{o}C$ to $-24^{o}C$.

The C-CORE impulse radar operated well with only minor problems. Calibration and playback of data was carried out in the field and good agreement was found with augered thicknesses.

The prototype EM system appeared to work satisfactorily, although intermittent problems were encountered on two of the three frequencies. Substantial time was spent to ensure that calibration and phasing were

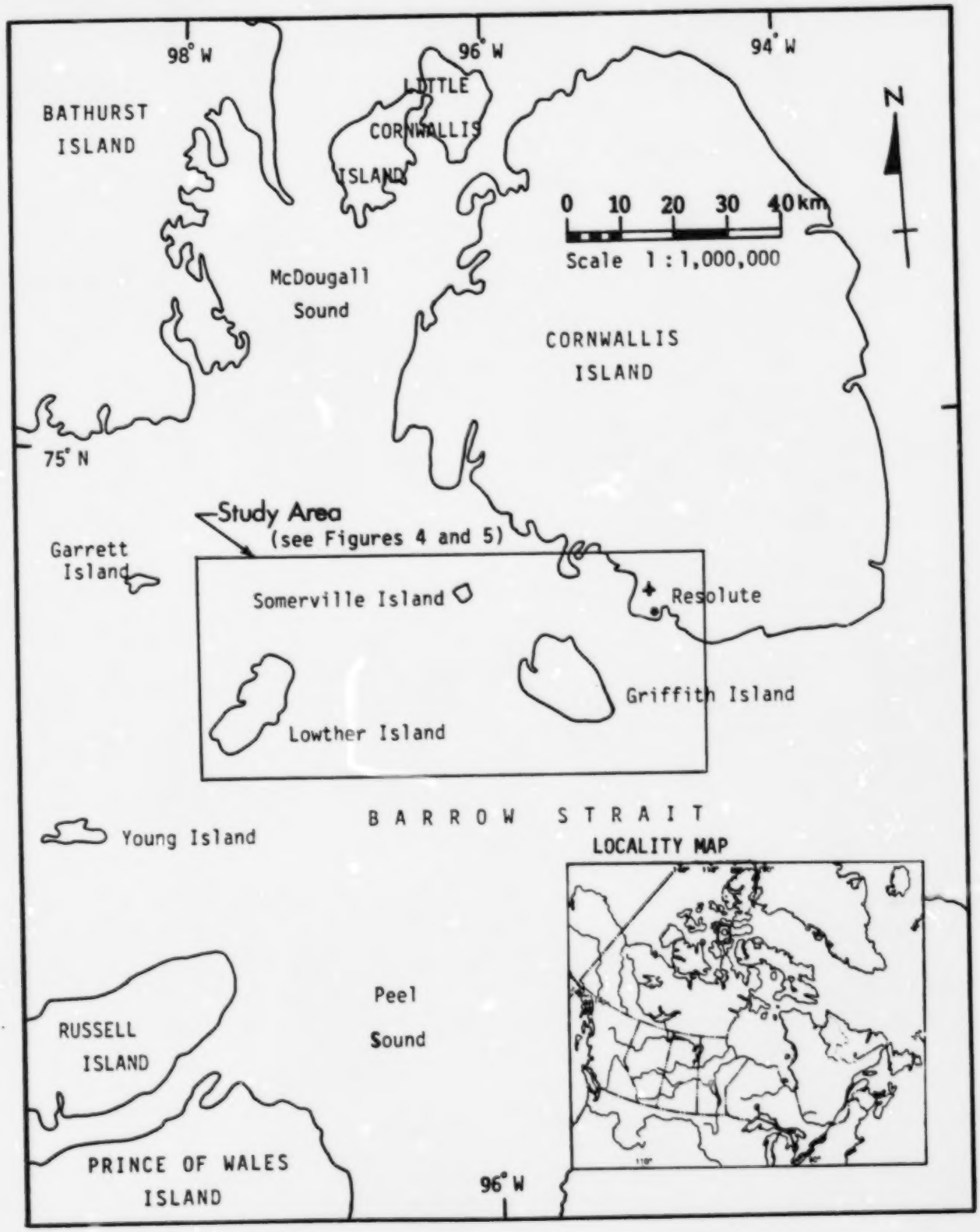


Figure 3. Location map.

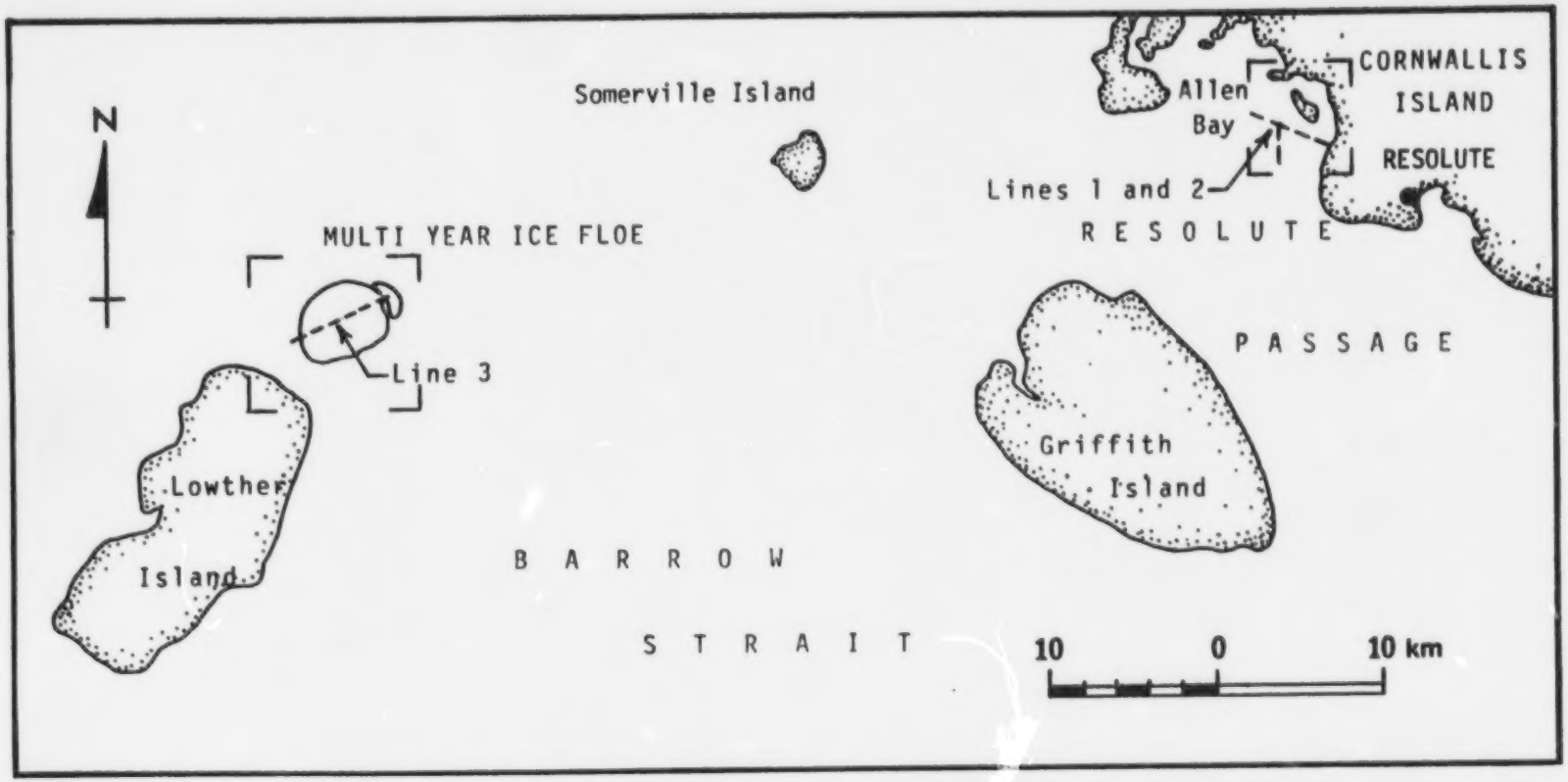


Figure 4. Map of study area illustrating survey sites (Lines 1, 2 and 3).

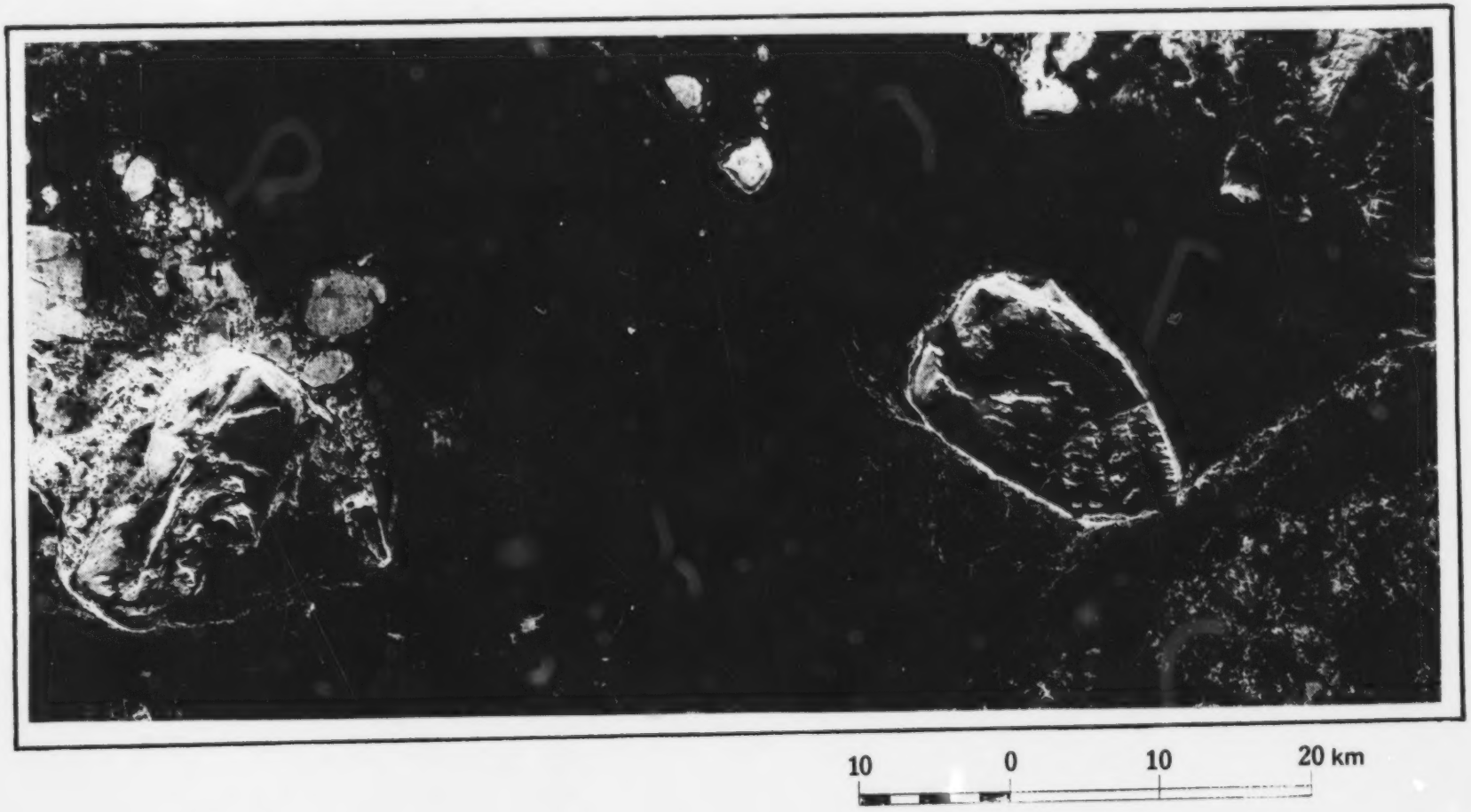


Figure 5. STAR-2 wide-swath SAR image of study area taken on February 15, 1987. [courtesy of Canarctic Shipping Company Limited].

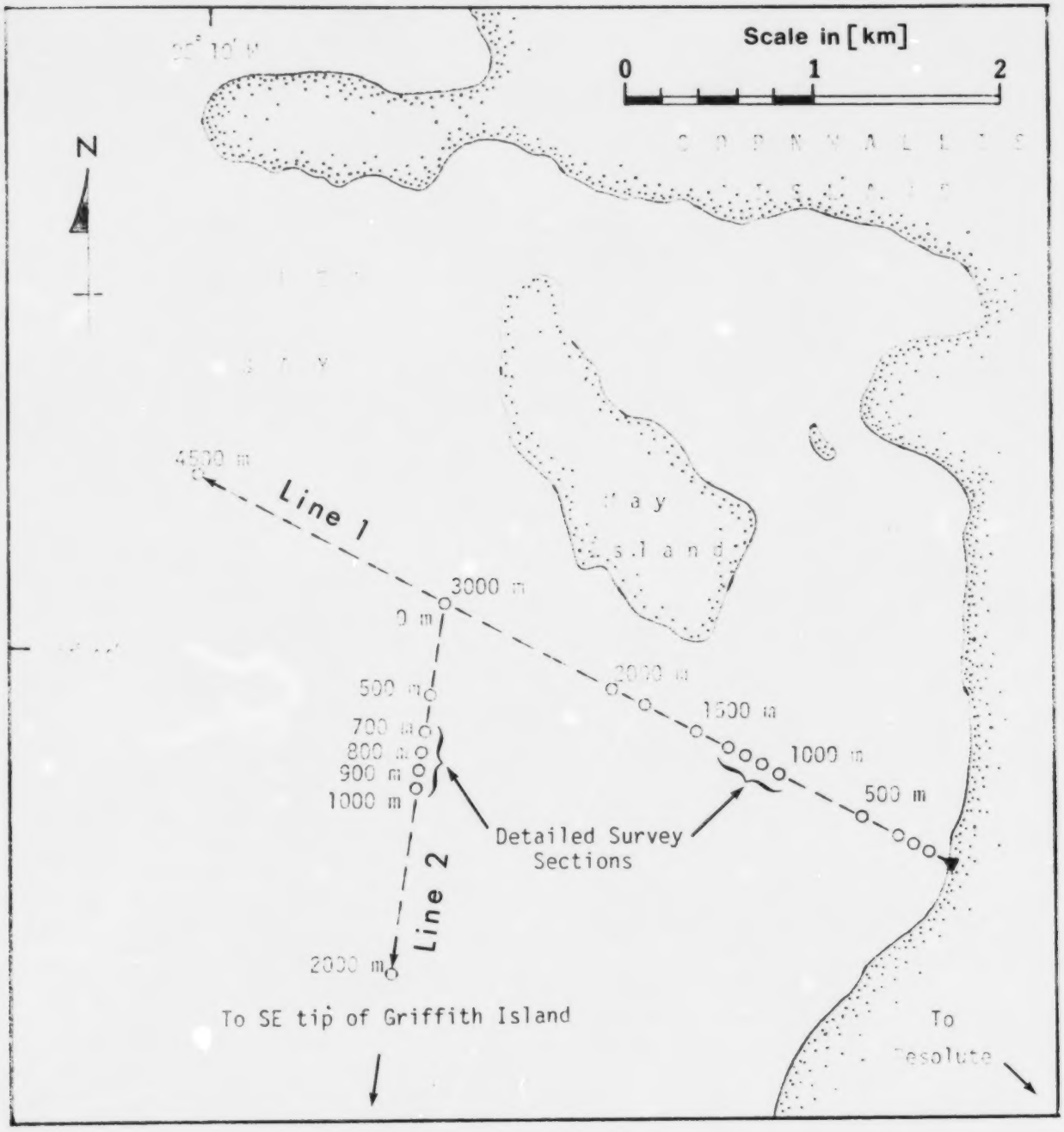


Figure 6. Detailed map of primary field site, Lines 1 and 2 over first-year sea ice in Allen Bay.

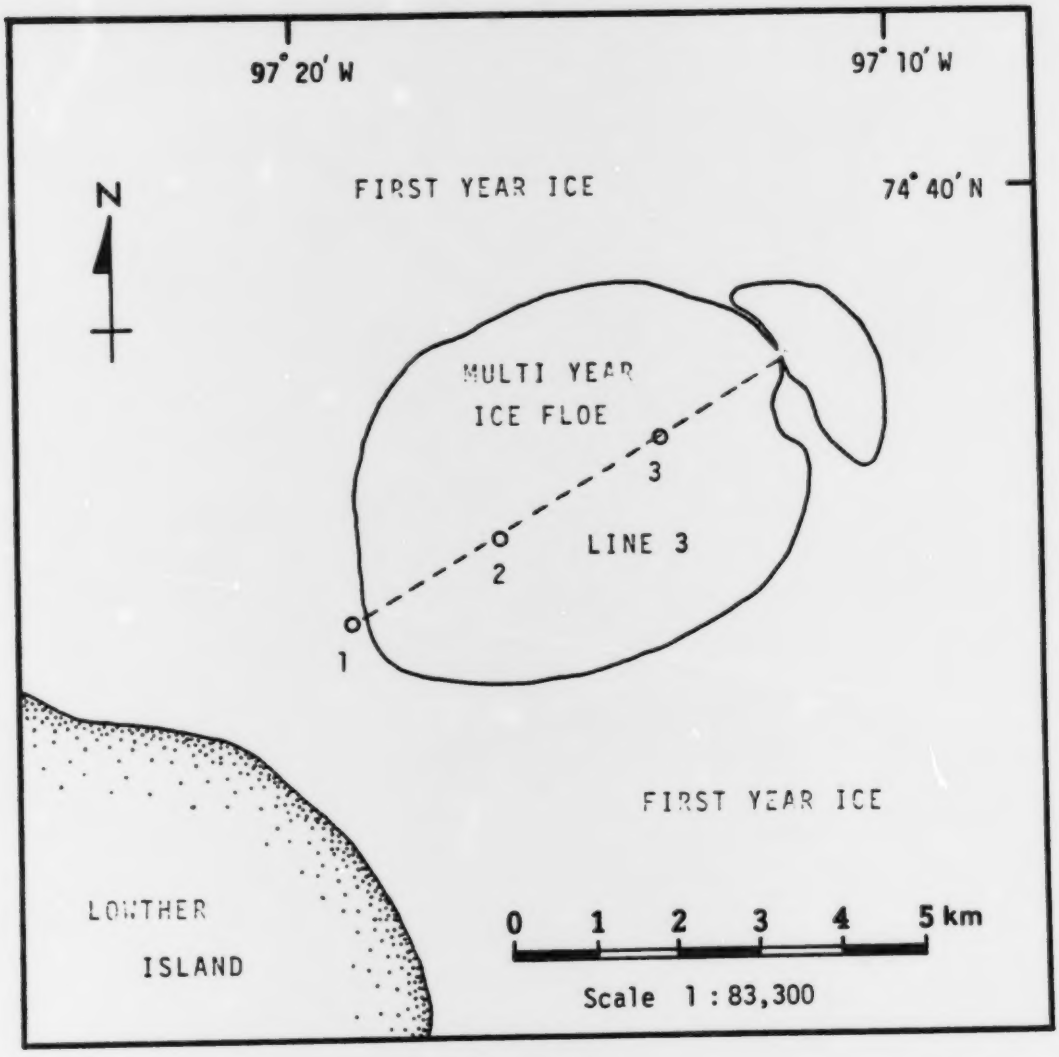


Figure 7. Detailed map of Line 3 over a multi-year ice floe near the NE tip of Lowther Island.

accurate and all truthed lines were flown at least twice for data redundancy. Although raw data were printed in the field, data could not be interpreted on site as no computer was transported to the field.

The MPB radar system was not operational. Problems with the transmitter, wiring, intermittent connections in the receiver, and antenna connectors were all repaired in the field. However one of the receiver modules failed and the fault could not be diagnosed. The antenna was mounted on the helicopter, but could not be flown because of weak and broken welds at several joints.

3.3 Data Collection

In total, ice and snow thicknesses were augered at 42 locations, and 80 ice and snow salinity samples were measured. Numerous 35 mm photos and videotape recordings were made. Salinity-temperature-density (STD) casts were also made in Allen Bay to obtain water conductivity, temperature and depth information. Snow and ice samples, in the forms of cuttings and shavings respectively, were taken from various depths at each augered site and were measured for salinity at base camp using a YSI-33 salinometer.

In addition, three long aerial traverses, approximately 100, 60, and 140 km, were made east, south and west respectively of Resolute over mainly level first-year ice and a large iceberg. No surface truth information was taken along these lines, but the ice appeared uniform on both Intera's SAR imagery taken February 15, 1987, and on the impulse radar record.

An additional line was located about 15 km SW of Resolute where a biology team was working and could provide detailed snow thickness over a 200 m line [12] (see Appendix A, Table A-4).

All of these lines and traverses were flown with both the impulse radar and EM systems separately. Although exact routes were not duplicated by the two survey systems on the long traverses, the positional errors over the survey lines are believed to be small because ground markings (bags) were used to guide the aerial traverses. Any travel deviation between surveys may be attributed to difference in travel speed of the helicopter.

3.3.1 Line 1

A base survey line, designated Line 1, was laid out over first-year ice in Allen Bay. The Line follows a northwest direction out from Resolute airport and commences at the shore (Figure 6). Approximately 4,500 m in length, this line was marked by bags every hundred metres over the first 2,000 m, and every 500 m from the 2,000 m mark to the end of the Line. Surface measurements were acquired at most bag locations. Between the 1,100 m and 1,300 m marks, holes were augered every 20 m .

Refer to Table A-1 in Appendix A for tabulated results. The average thickness of sea ice along the Line was 2 m, with a lowest value of 1.62 m

at the 1,200 m location and a highest reading of 2.45 m at the 1,300 m mark. A small iceberg fragment was encountered at 3100 m.

3.3.2 Line 2

Line 2, a branch to Line 1, was laid out in a southward direction (toward the southeastern tip of Griffith Island) from the 3,000 m station of Line 1 (Figure 6). Approximately 2,000 m in length, this Line was delineated by bags every 500 m with additional markings at the 700, 800, and 900 m points. A detailed section of drilling was performed between the 700 m and 900 m sites with holes augered 20 m apart.

The average recorded thickness of ice along Line 2 was just over 2 m with the thinnest point (1.8 m) at the 0 m mark (or 3,000 m point on Line 1) and the thickest point (2.19 m) at the 740 m location. Refer to Table A-2 in Appendix A for a detail summary of surface measurements along Line 2.

3.3.3 Multi-Year Floe

The multi-year ice floe near the northeastern edge of Lowther Island was laid out with a line oriented along a southwest to northeast axis approximately 5.4 km in length (Figure 7). Three surface measurement stations were marked by bags. Holes were augered and salinity measurements were made at each of these sites. Station 1 was situated near the starting point of Line 3 (southwestern edge of floe), and stations 2 and 3 were located approximately 1,900 m and 3,900 m along the line, respectively. These stations were chosen at thin points on the floe in order to optimize drilling effort, and therefore cannot be used to estimate the floe's average ice thickness.

Tabulated surface results can be found at the end of the report in Table A-3 in Appendix A.

4. DATA ANALYSIS

The primary objective of the data analysis was to determine the ice thicknesses along the main traverse lines as determined by the two operational sensors. These results could then be compared to the surface information and to each other (Chapter 5). In addition, other features of each of the data sets were examined in order to try to understand them better.

4.1 Surface Measurements

Most of the analysis on the surface measurements were made in the field. Snow and ice thicknesses and salinities at each measurement point were tabulated.

In order to try to understand the discontinuity in the first-year ice along Line 2, salinity-depth information was plotted as shown in Figure 8. It must be recognized that the uncertainty in salinity measurement is $\pm$ 0.25 parts per thousand (ppt) and that possible errors in depth are $\pm$ 0.2 m. In addition, since samples were taken from auger cuttings, there is potential for contamination as the cuttings are raised to the ice surface and collected. Therefore the results are approximate, but do show a transition in the salinity of the ice at approximately the 750 m position, with a slightly higher salinity further from shore.

4.2 Impulse Radar

For most of the runs collected it was possible to estimate the ice thickness directly from the visicorder plots by identifying the ice top and bottom echoes, and measuring the distance between them (Figures 9, 10, 11). Since the total window (either 90 or 360 ns) was known (see section 4.2.4), the appropriate scaling could be applied to the plots. The travel-time can be converted into ice thickness using the formula.

$$d = \frac{vt}{2} \qquad (1)$$

$$= \frac{ct}{2k^{1/2}} \qquad (2)$$

where d is ice thickness (m)
v is the propagation velocity in ice (m/s)
t is two-way travel time (s)
c is the speed of light (3×10^8 m/s)
k is the dielectric constant of ice.

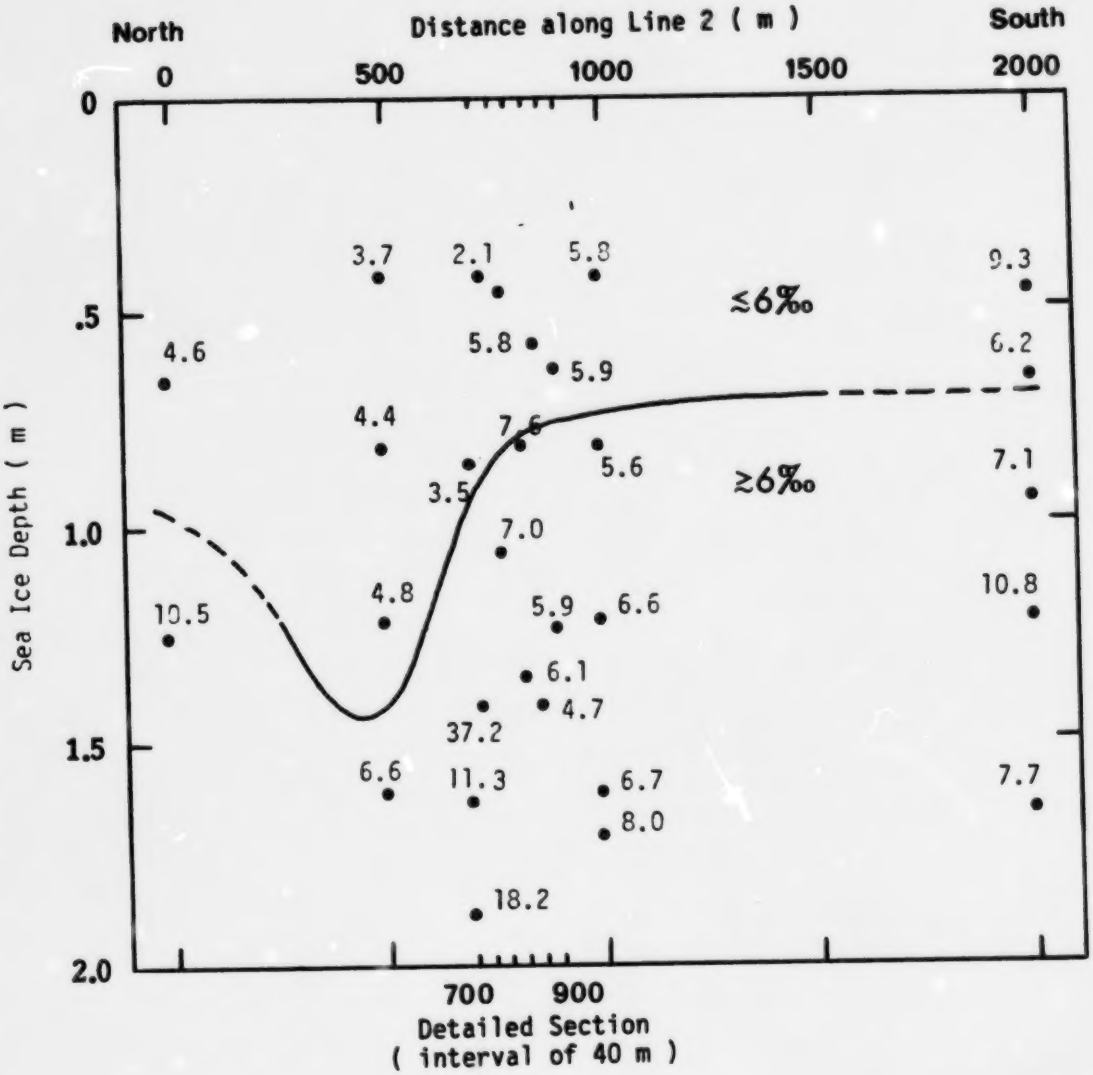


Figure 8. Ice salinity profile along Line 2.

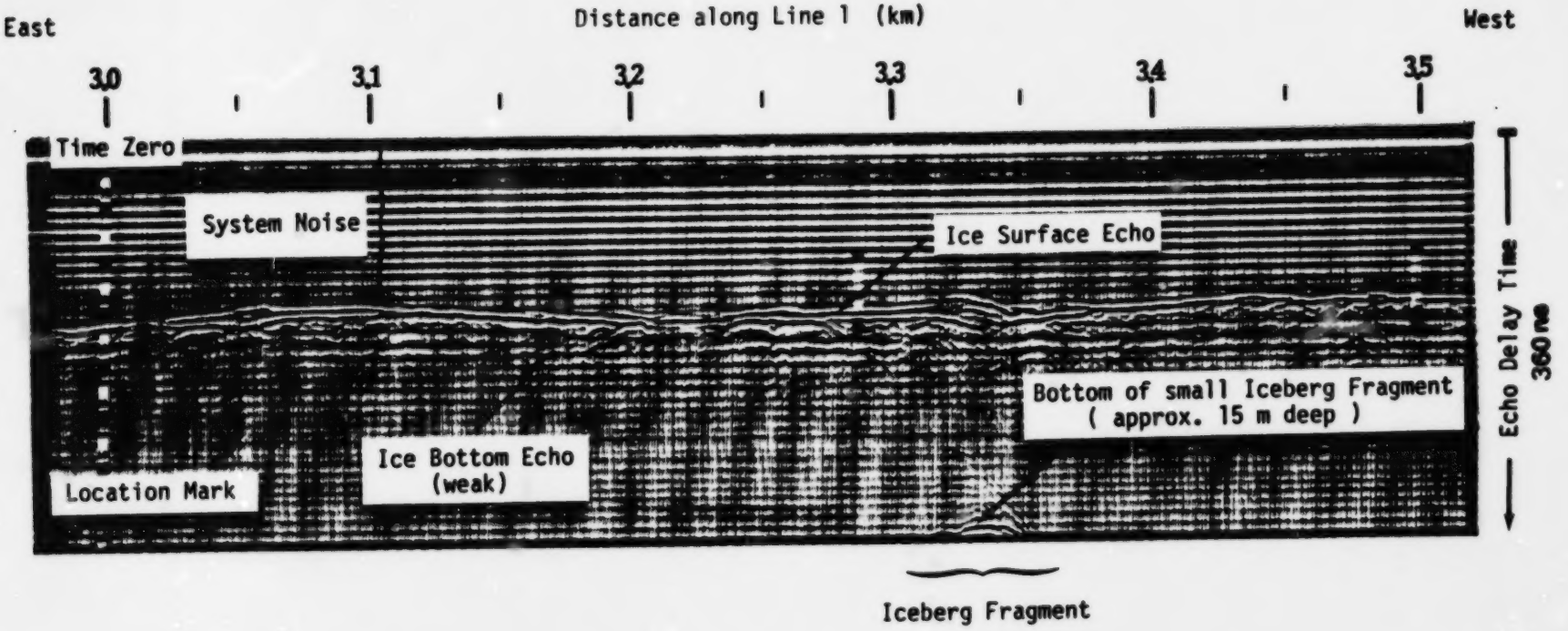


Figure 9. Visicorder grey-level strip chart of the impulse radar profile for the 3.0 to 3.5 km portion of Line 1.

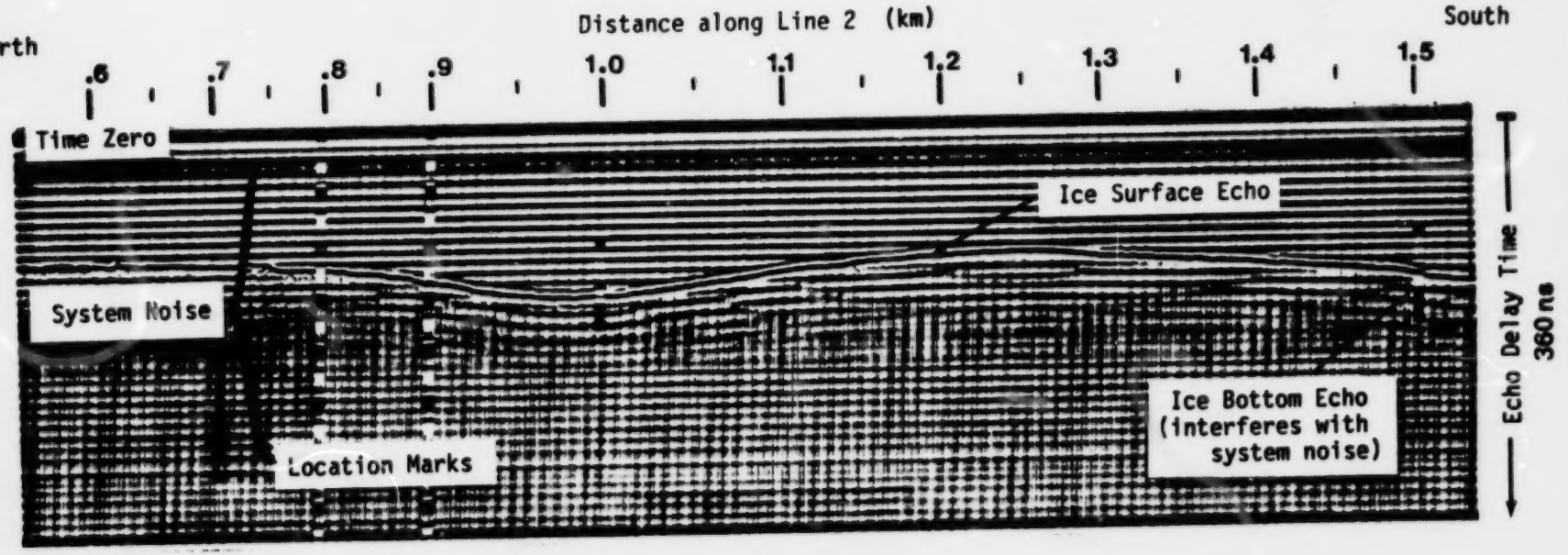


Figure 10. Visicorder grey-level strip chart of the impulse radar profile for the 0.6 to 1.5 km portion of Line 2.

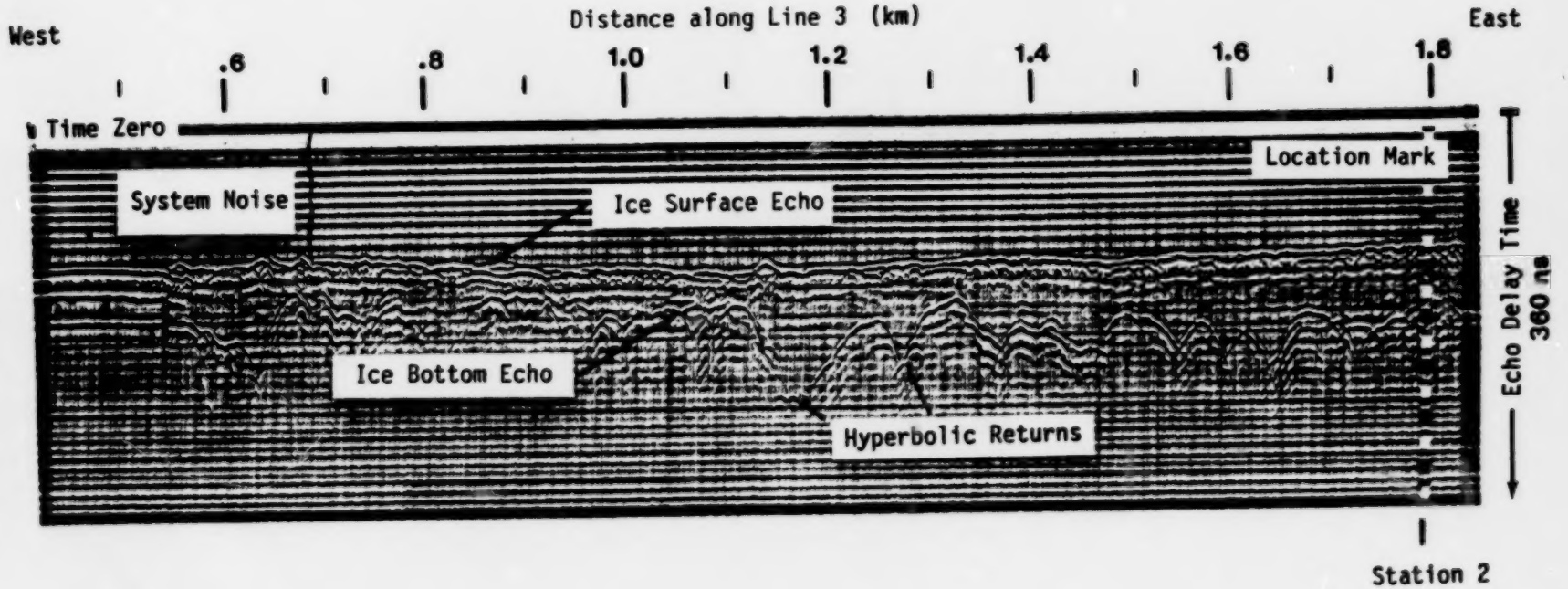


Figure 11. Visicorder grey-level strip chart of the impulse radar profile of multi-year ice between stations 1 and 2 along Line 3.

For most first-year sea-ice k is 4 to 6 [14] and a value of 4 was used throughout. Errors in estimation the correct value for k will lead to systematic under- or over-estimation of ice thickness. However, since the dielectric constant enters as a square root, the possible error is usually no more than $\pm$ 10%, and can be improved by using a better estimate for k (e.g. from an augered ice calibration point).

As seen in Figures 9 and 10, a weak ice bottom echo is often difficult to discern from the visicorder plots, especially when the returns are masked by system noise. This problem is usually due to attenuation or scattering of the radar signal by the ice, and can be overcome to some extent by computer processing (section 4.2.2).

The multi-year line (Line 3) had continuously changing thickness of ice which could be measured directly from the visicorder plots. Line 1 had very consistent ice thickness. Changes in the height of the helicopter over Line 1 allowed the radar returns from the ice to be seen in amongst the ringing. Most of Line 2 had very uniform ice because the helicopter flew very steadily, thus effectively hiding the returns in the ringing without processing.

Scattering from a point target produces a distinctive hyperbolic echo. This type of echo is caused by rough features on the ice surface, bottom, or occasionally within the ice itself. The rougher multi-year ice data, shown in Figure 11, have hyperbolic echoes in many places. The hyperbolic shape is controlled by the antenna beam pattern and position geometry, and is not indicative of the actual shape of the feature.

4.2.1 Recording and Analysis System

The data were recorded on two channels: the radar reflection information on one, and the synchronization pulse indicating the start-of-scan position for each trace, on the other. In the digitization procedure, the sync pulse was sent to the computer controlling the analog-to-digital (A/D) conversion to begin sampling the data until enough samples were taken for each given scan. This step continued until the available memory for the A/D process was filled.

The hardware used in the digitization process was an IBM-PC compatible computer with a Data Translation DT2801 A/D converted installed in it. The ASYST (version 1.51) signal analysis package provided routines which are tied together in a program to control the A/D conversion. The ASYST package allows only 64 kilobytes of memory to be used in any one acquisition attempt. The DT2801 A/D converter was software programmed to convert the data a 12 bit resolution across a voltage range of -5 to +5 volts. Each scan had 185 sample points and 170 scans were collected before the 64 kilobytes memory limit was reached. IBM-PC compatible computers (models AT and XT) running the ASYST signal analysis package and Turbo Pascal with IBM compatible graphics printers (Admate) provided the environment for handling the digitized data.

4.2.2 Computer Analysis

Blocks of data, 64 kilobytes in size, were digitized at each ice surface measurement station, and several procedures were used to enhance the ice top and bottom echoes. First, a DC offset was removed using a high pass filter. Second, a slight data jitter problem was reduced using a routine to align the first peak in the data. Third, in areas of uniform ice thickness, stacking (or averaging) of several traces together, provided improved signal-to-noise.

Systematic ringing noise was present in the data which can be seen in the visicorder plots as multiple continuous dark and light bands remaining constant in the time window and continuing trace after trace (Figures 9-11). For some reason the Background Noise Removal device was not effective. Therefore, this noise was subtracted after the field trip using a background data block collected when the helicopter flew high enough (greater than 54 m altitude) that the ice echoes were beyond the data windows (360 ns). This step allowed significant improvement in the detectability of the ice top and bottom echoes, as shown in Figure 12. Echoes buried in the system noise are easily seen after processing.

4.2.3 Flight Path Recovery

While flying the lines collecting data, references of the helicopter's position to the line were made several ways.

The C-CORE Impulse Radar unit has two marker buttons that puts two recognizable marks in with the data. These marks are called the 0-mark and the 1-mark. These marks show up during playback on the visicorder.

The VCR records the data on 2 FM audio channels and also records a signal from a downward looking video camera. When played back, the video showed the locations of markers on the ice at the same time as the visicorder plotted the impulse radar returns for that point and could be used to verify the manually inserted marks.

Voice recordings made during flight have information on the time and the

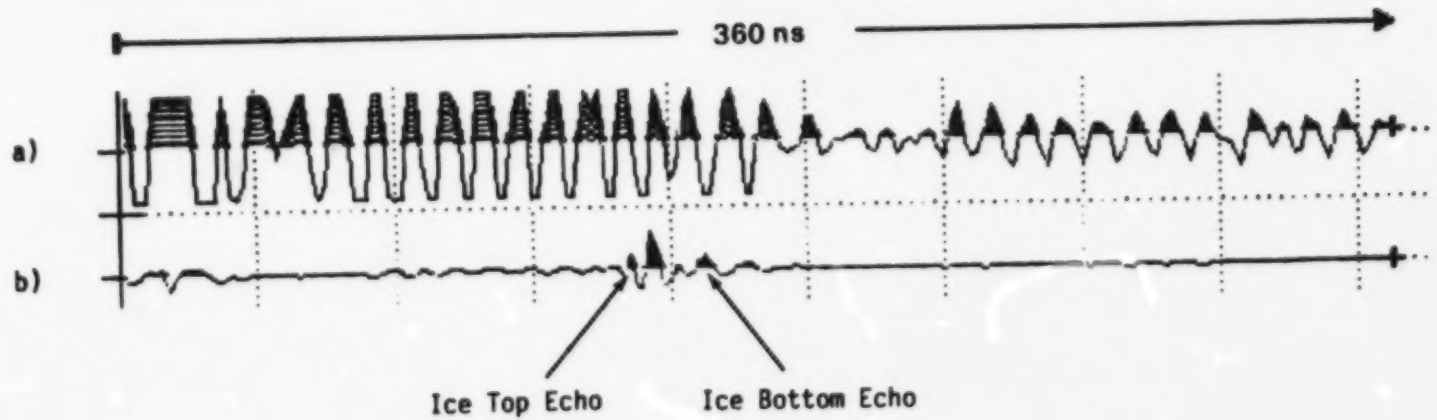


Figure 12. Example of impulse radar returns at 800 M on Line 2 before and after computer processing. After processing the echoes can be picked easily.

a) High-pass filtering only.

b) High-pass filtering; peak alignment; averaging; and background removal.

tape counts along the lines. This served as another cross reference of the helicopter's location.

4.2.4 Calibration

The time window in which the impulse radar returns are seen start a few nanoseconds after the transmit pulse is fired and extends for either 90 or 360 ns (switchable). When the data are played back on the visicorder or when it was digitized, the size of the window is no longer precisely known. On the ground at Resolute, tests were made to allow the played back windows to be calibrated.

Using a hanger door as a target, with the impulse radar antenna on its side, a data set was collected for each window length. The antenna was moved back from the hanger at discrete distances. When played back, the length of the window on the visicorder or the length of the digitized trace can be calculated.

4.3 EM Induction

In order to determine ice thickness from the EM data, three operations were required: transcription of the data from field tapes to "RAW" disk files, reduction of the raw data to files ready for interpretation, and interpretation of the data. Until recently, the data reduction step was the slowest part of the process because it required a significant amount of human intervention. However, now that data reduction has been automated, reduction of the data from a given flight now takes less than a man-hour, compared to approximately 8 man-hours with the previous data-reduction software. This time is now comparable to the time required for the interpretation of the reduced data files.

4.3.1 EM Data Reduction

In preparation for the data reduction operation, the survey data are read in from the tapes written in the helicopter by the data acquisition system. This step is actually a translation and reformatting of the field data rather than a simple copying operation. The result is an unformatted raw data file containing the relevant data set for an entire flight.

This data file is then read by the Master Calibration (MASCAL) program, which presents the information graphically. The analyst selects the high-altitude sections of the data most suitable for drift calculations, and MASCAL compiles them and writes the results into calibration control (CAL) files, one for each survey pass in the flight. High altitude sections are sought because the system should be sensing negligible amounts of secondary field at these times: any change observed during successive high-altitude (or "zeroing") sections may be attributed to system drift. A variety of other information is also contained in the CAL file, such as the amplitude and phase calibration factors for each frequency. When the drift

information for each line in the flight has been written out, the analyst runs the reduction routine for each line. In this routine, the linearly interpolated drift value at each sample time (and for each frequency and phase component) are subtracted from the observed raw data. The data are then scaled using the amplitude and phase calibration factors mentioned earlier. The factors relate the desired response of the system in parts per million (ppm) of the primary field amplitude at the receiver to the output of the data acquisition system given in bits.

Estimation of these scaling factors forms the calibration operation. Two methods are presently in use. The first, known as "external phasing and calibration", utilizes a ferrite bar and an external Q-coil to provide the calibration signals, and is performed on the ground as part of preflight checkout. Phasing is normally carried out first: the ferrite bar is moved into and out of alignment with the primary field of the coil pair being phased. Since the ferrite material is effectively an insulator, only the inphase component of the secondary field changes as the bar moves from maximum to minimum coupling. The receiver console is adjusted to minimize variation in the out-of-phase or quadrature component due to changes in bar orientation.

When all frequencies have been phased (they are normally phased one at a time), the system is ready for amplitude calibration. The external Q-coil is set up on a jig attached to the bird, with its centre at a precisely known distance from the receiver coil being calibrated. This Q-coil is a precisely tuned R-L circuit of known effective area. When this circuit is closed by means of a switch, it generates a known secondary field at the receiver coil. Alternate opening and closing of the circuit provides a set of calibration pulses of known size (in ppm) which are used to set the gain of the analog console. This type of calibration permits estimation of the scaling factors to about 1% in phase and about 10% in amplitude.

The ground-truth calibration technique is normally used as a correction for the initial calibration obtained during external calibration. In this procedure, the bird is flown over a series of known stations on the ice where the ice thicknesses and sub-ice water depths are known, normally as a result of drilling and lead-lining. The measured EM responses (calibrated externally) over these sites are compared to those calculated for the sites using a forward model routine and the known characteristics of each site. If discrepancies are observed, a new set of calibration factors are calculated using the old values and the observed deviation. If a good site is used, the accuracy of this technique is relatively nigh; about 1% in both amplitude and phase. The best types of sites for performing this type of calibration are, in order of desirability, deep, open water, flat new ice over deep water, and flat ice over known sub-ice water depths. Where ice is present, its thickness must be known to within a few centimetres, as any errors in ice thickness will bias all subsequent interpretations.

Flight path recovery is a straightforward, if somewhat time-consuming process. Points of interest (usually ground-truth sites) are marked on the ice with black garbage bags filled with snow: these can be identified from the air and used to orient the flight line. The video record of the flight

can be analyzed later to determine when the bird passed the marks, which yields a set of fiducial numbers corresponding to bag locations. Lateral deviations from the desired flight path are harder to assess unless a grid of black bags has been laid out on the ice to serve as a reference.

4.3.2 EM Data Interpretation

The technique used to interpret the EM data is based on damped least-squares method [13] of nonlinear regression. The method depends upon having an accurate forward model which predicts the EM response of an earth model given the geometrical and electrical properties of the EM system and the earth model. The earth model used for this interpretation is a horizontally-layered, isotropic halfspace, in which different layers possess distinct conductivities and thicknesses. This forward model is used in two ways: first, for comparison with the measured EM response to determine how well the model agrees with the actual earth structure; and second, to generate a set of partial derivatives (the Jacobian matrix) of each measurement with respect to each model parameter being sought. This matrix is often poorly-conditioned, and must therefore be inverted using generalized inverse techniques [13], and used to predict the change required in the target model parameters (in this case ice thickness and perhaps water depth) to make the model response agree with the observed data. Since the forward model is a nonlinear function, this correction is never exact, and an iterative process is required to converge on the optimal values (in the sense that they minimize misfit of the model response to the observed response) of the model parameters.

Aside from the mechanics of performing this regression efficiently and accurately, a variety of checks and controls on the inversion process are required to prevent the regression from becoming unstable when noise or other data problems arise. In other cases, it is necessary to provide some human intervention during the interpretation process. For example, in some of the data gathered during the 1987 field work, drift in some frequency channels was problematic. The technique used to sidestep the problem was to simply ignore those data channels and concentrate on the frequencies that worked best. Fortunately, most of the survey work was over fairly deep (more than 10 metres) water depth where little variation in the EM response due to water depth was visible. Water conductivities also appeared to be constant over the area. Under these circumstances, it was possible to reduce the number of target parameters from the usual three to one.

4.4 Synthetic Aperture Radar

A limited amount of analysis was carried out on the Star-2 data (Figure 5). Sites were selected corresponding to areas of different brightness intensities on the imagery, and the actual digital signal levels within these areas were measured using an Aries Image Analysis system. The signal levels were then converted into dB and relative signal strengths determined. The results are given in Table 3.

Using the relatively dark first-year ice as a reference, the first-year ice on Line 1 was approximately 1.0 to 1.6 dB brighter, and the multi-year ice was 4.3 to 4.7 dB brighter. In a very coarse way, higher salinity ice appears darker in the SAR imagery.

Table 3. Digital SAR reflectivity values showing the contrast between first-year and multi-year sea ice.

Location (Distance in m)	Count	Reflectivity (dB)
Line 1 First-year		
500 - 1,000	14	1.08
1,500 - 2,000	15	1.26
3,000 - 3,500	16	1.44
4,000 - 4,500	17	1.62
Line 2 First-year		
1,000 - 1,500	8	0
Line 3 Multi-year		
Site A (reference)	8	0
Site B	30	4.32
Site C	34	4.70

5. DATA INTERPRETATION AND COMPARISON

The object of this analysis was to evaluate quantitatively the effectiveness of the two airborne ice profiling technologies in measuring sea ice thickness. Two approaches were used in the evaluation. The first approach involved comparison of the impulse radar and EM induction interpreted results with surface measurements. The second approach analyzed the intercomparison data statistically using a first-order linear regression analysis.

5.1 Ice Thickness

Figures 13, 14 and 15 results show representative ice (or ice plus snow) thickness profiles along Lines 1, 2 and 3 respectively. The top plot (a) in each figure shows the augered measurements of ice thickness compared to an impulse radar profile. The middle and bottom plots (b and c) depict snow plus ice measurements compared to two separate EM profiles.

The impulse radar and auger results are in close agreement, within $\pm$ 20 cm in most cases, using a dielectric constant of 4 for the ice. Repeated lines were very similar to each other. In some sections the bottom echo was lost, and in one case the echo was outside of the window used (Figures 9, 10, 11). These results are in keeping with previous results using impulse radar over sea ice [15].

The EM results were more variable than the radar, and agreement was usually within $\pm$ 50 cm after removing data glitches, poor calibration and drift. These problems are due to use of a prototype system, and are not believed to be inherent to the technique. Major features on each line were duplicated repeatedly from run to run. The variability in the run to run results is largely explained by inability to keep the helicopter and/or towed bird exactly on the nominal flight path for each pass.

5.1.1 Line 1 - First-year Ice

The EM survey runs along Line 1 (Figure 13b and 13c) were affected in varying degrees by non-linear drift problems which typically had the effect of altering the average ice thickness for the entire Line, and in some cases introducing a gradient in the ice thickness over the length of the Line. However, in all runs the details of ice thickness were picked up quite well. The principal feature, visible on all runs, is a piece of iceberg ice frozen into the first-year ice near the 3100 m mark.

5.1.2 Line 2 - First-year Ice

As illustrated in Figures 14b and 14c, of the two EM runs over Line 2, only in Figure 14c can the transition between the possibly slightly older first-year ice at the northern end of the Line and ice to the south be seen, although there is some indication of the same apparent thinning near the

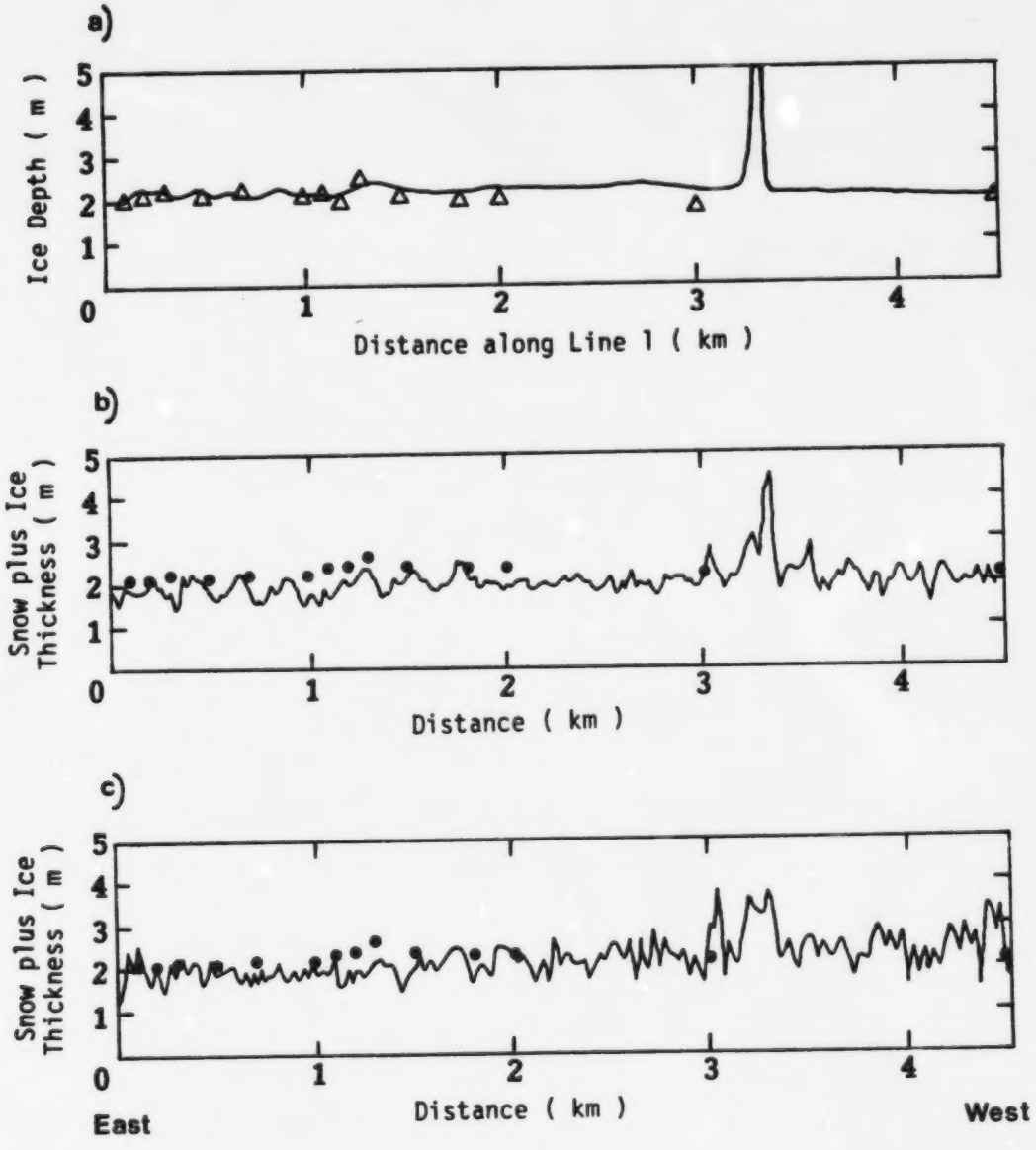


Figure 13. Ice and snow plus ice thickness profiles along Line 1 as observed by impulse radar (a), and EM induction (b) and (c). Surface measurements are denoted by Δ for ice depth, and ● for combined snow and ice thickness.

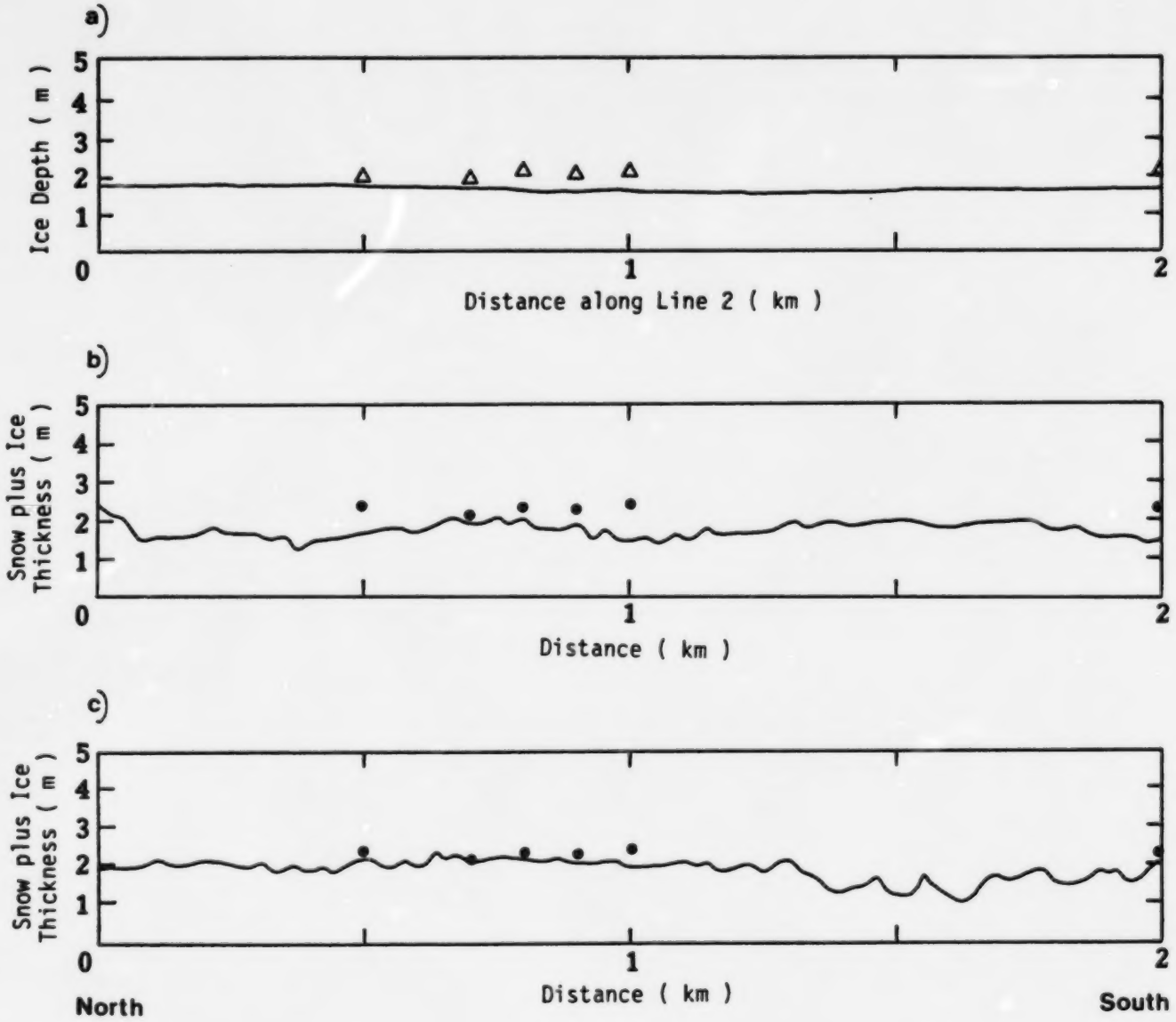


Figure 14. Ice and snow plus ice thickness profiles along Line 2 as depicted by impulse radar (a), and EM induction (b) and (c). Surface measurements are represented by △ for ice depth, and ● for snow plus ice thickness.

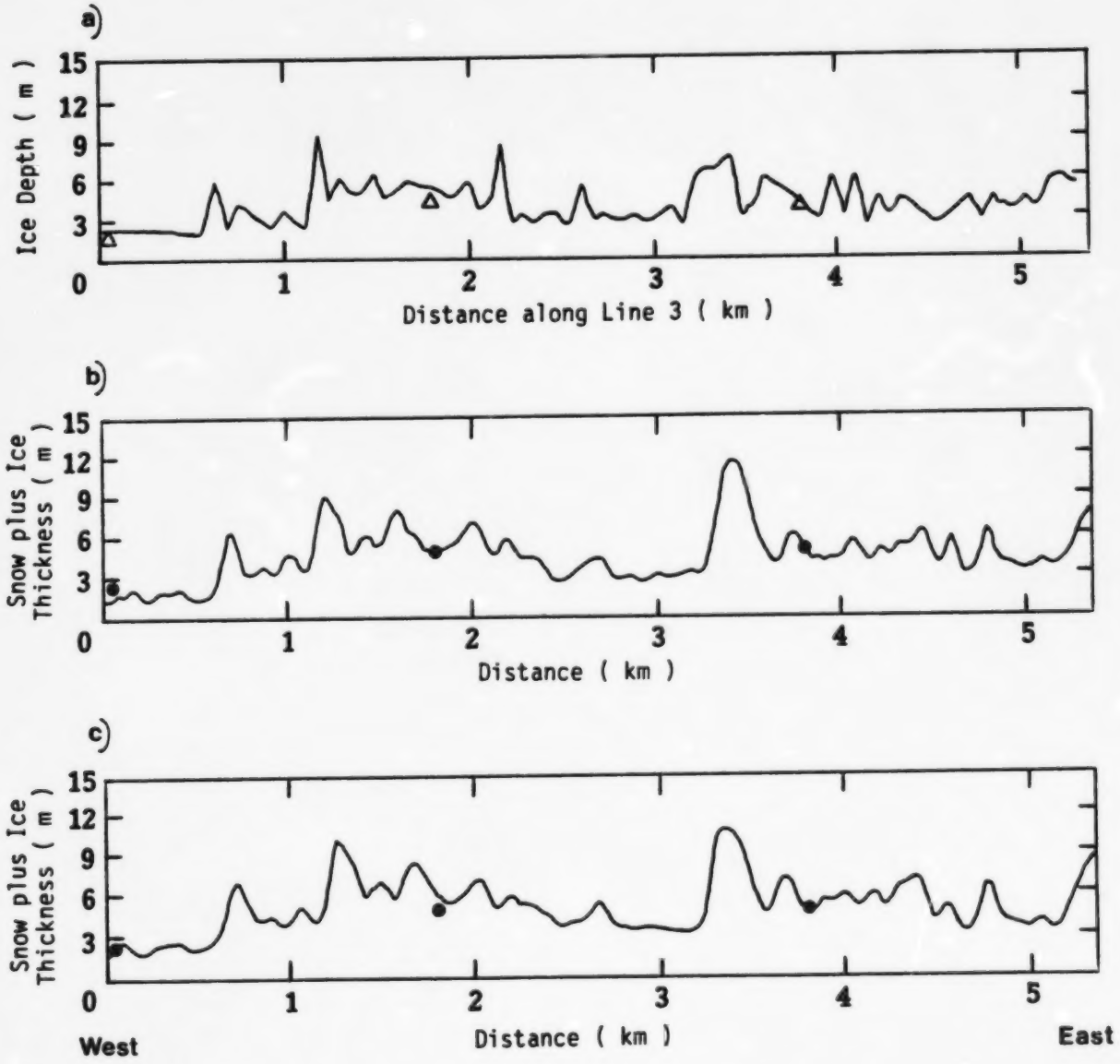


Figure 15. Ice and snow plus ice thickness profiles along Line 3 as observed by impulse radar (a), and EM induction (b) and (c). Augered surface measurements are denoted by △ for ice depth, and ● for combined snow and ice thickness.

500 m mark in Figure 14b. Unfortunately, Line 2b was flown at a somewhat greater altitude than Line 2c, which resulted in irregular ice thickness estimates near 1000 m and south of 2000 m.

5.1.3 Line 3 - Multi-year Ice

The multi-year floe exhibited a fairly rough surface topography, which implies substantial variation in overall ice thickness. Since this variation is three-dimensional, it is most unlikely that successive EM overflights of the survey line would produce identical ice thickness profiles. This is in fact the case: although most of the large features were reproduced faithfully from run to run, the details of the profiles varied (Figures 15b and 15c). Another factor complicating comparison of individual runs is that the flights were made at different speeds, which means that the interpreted ice thicknesses must be plotted on different horizontal scales to make the augered sites plot together. Since ground speed undoubtedly varied along each run, there is also some compression and expansion of individual features which are difficult to separate from similar variations due to lateral shifts in the flight line.

Drift in the EM data for Line 3 was not found to be severe, probably because the equipment had ample time to warm up during the flight out to Lowther Island from Resolute.

5.2 Statistical Comparisons

Impulse radar ice depth estimates along Lines 1, 2 and 3 were compared with coincident augered surface records. A linear least-square regression analysis was applied to this set of data pairs. A scatter diagram depicting the correlation between radar and ground data is given in Figure 16. A radar to ground, 1:1 line of perfect agreement, was placed for reference. Assuming the surface data to be the independent variable, the resulting regression line has the form:

$$R_i = 0.325 + 1.157S_i \qquad (3)$$

where R_i represents the radar estimate, S_i the surface measurement, and the subscript "$_i$" denotes ice depth. The correlation coefficient between the two sets of data is very high, $r = 0.919$. Considering the small sample size ($n = 23$) and the clustering of measurements about the 2 m depth mark, the regression results are good. A slope of 1.157 and a y-intercept of -0.325 m suggests that radar slightly over-estimates ice depths greater than 2 m, probably because the dielectric constant used was slightly low. However, it should be noted that no conclusive inferences can be derived from these results due to the small sample size and relatively large number of points about a single ice thickness.

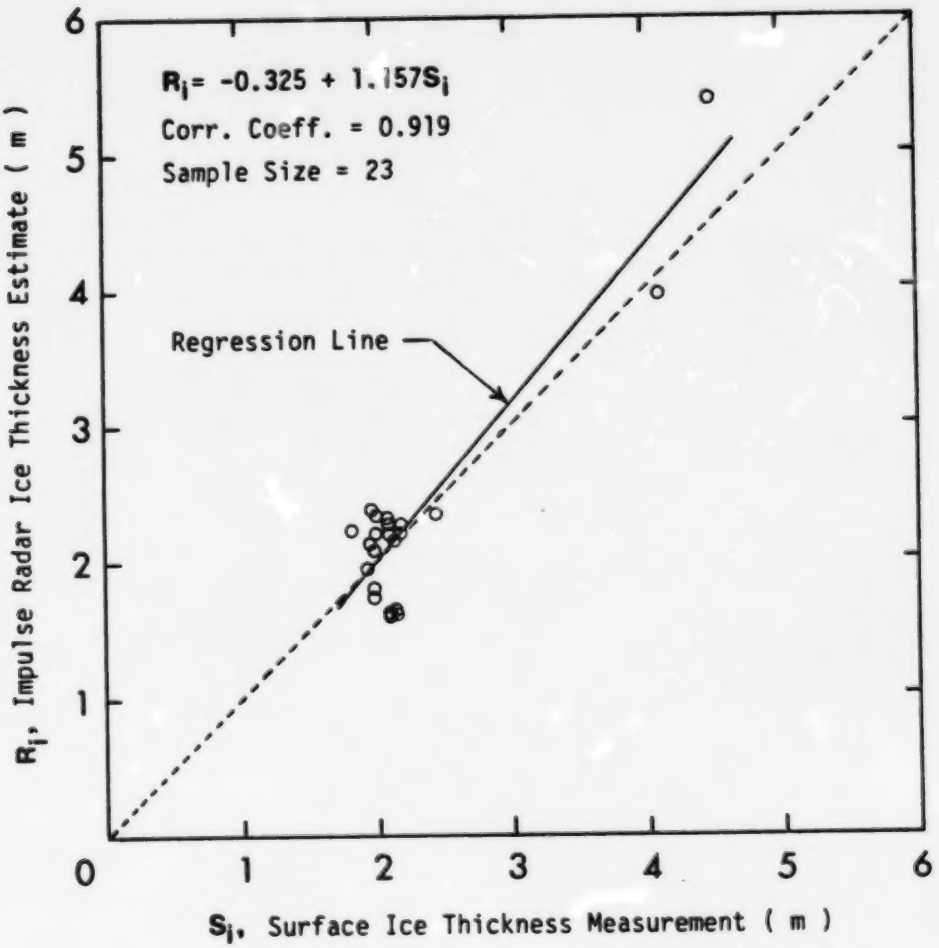


Figure 16. Scatter diagram comparing airborne impulse radar sea ice depth estimates with augered measurements. Dashed line is a reference line representing the 1:1 line of perfect agreement.

A similar scatter diagram compares EM derived snow ice depth estimates to surface measurements (Figure 17). The EM on ground regression line, assuming the surface to be the independent variable, has the form:

$$EM_{si} = -0.733 + 1.194S_{si} \quad (4)$$

where EM_{si} is the electromagnetic estimate, S_{si} the surface measurement, and the subscript "si" refers to snow plus ice thickness. Using a sample size of 46 data pairs the EM results were found to be strongly correlated with surface measurements, exhibiting an r value of 0.946. It should be noted that twice as many EM sample points were analyzed here than for the impulse radar scattergram.

5.3 Discussion

It is fairly clear from the previous section that both the impulse radar and EM induction systems were able to effectively measure the thickness of the ice encountered during the field trials. In this section, some of the details of the responses will be discussed and comments on the applicability of the technologies to other operating environments will be made.

5.3.1 First-year Ice

From the SAR imagery (Figure 6) it can be seen that there are two fairly distinct first-year ice types. The SAR response along Line 1 varies from fairly medium grey through to some bright echoes towards the end of the line. Line 2 covers a boundary from grey to black response, which encompasses a reflection difference of approximately 1.6 dB. However, in general terms the thickness across this boundary does not change dramatically. We were interested in whether other records could indicate the presence of this boundary. The EM induction results do not show any indication at the boundary of a change. The impulse radar ice bottom echo does vary, changing from a smooth, weak echo over the darker ice, to an irregular, stronger echo near shore. The salinity of the ice further from shore was also somewhat higher.

Our speculation is that the ice near shore formed first under somewhat more turbulent conditions and that ice further from shore formed slightly later in the season under quieter conditions. This hypothesis is supported by the rougher ice surface having a brighter SAR return and a somewhat rougher ice bottom. However, the two ice sheets could not have frozen in place at greatly different times because their average thickness is not much different. The higher salinity of the darker ice would also give a more attenuated return for the SAR and the impulse radar. The higher salinity reduces the strength of the impulse radar bottom echo to a fading return which was not always easy to pick.

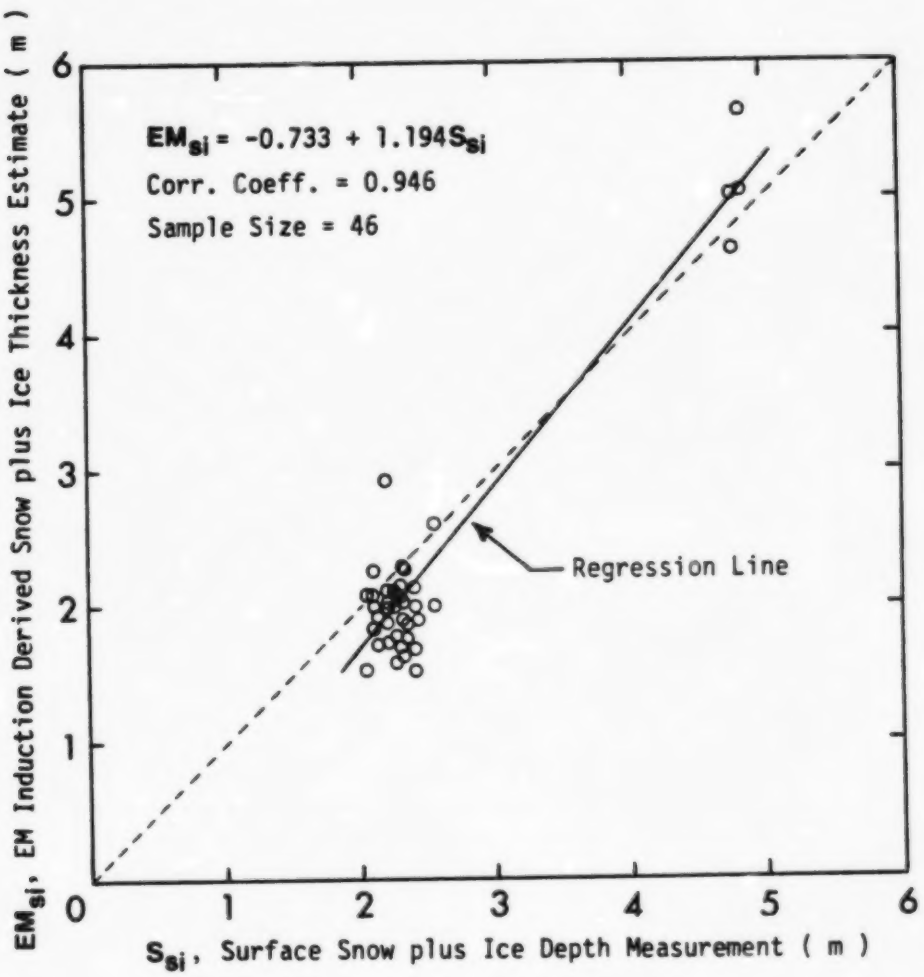


Figure 17. Scatter diagram comparing airborne EM induction snow plus ice thickness estimates with augered surface measurements. Dashed line is a reference line representing the 1:1 line of perfect agreement.

5.3.2 Multi-year Ice and Icebergs

Both the impulse radar and EM induction were able to effectively sound the multi-year floe which had relatively low salinity. Although holes were only able to be placed in relatively shallow portions, the agreement was good both with the surface measurements that were made and between the two sensors. There were not many sections of deformed ice in the area studied and it is not possible therefore to comment upon the effectiveness of the EM induction for this type of ice. However, from previous experience, it is known that impulse radar will not sound ridges with any reliability.

Pieces of fresh water ice found near Line 1 were also sounded effectively by both sensors. However, the impulse radar echoes were near the bottom of the window used, and had the ice been slightly thicker, the echo would have been out of the window altogether. This is an instrumentation problem, but is typical of some of the problems encountered with impulse radar.

5.3.3 Snow

Typical snow thicknesses in the area are given in Table A-4 in Appendix A. Using these 200 measurements, mean snow thickness was found to be 10.4 cm with a standard deviation of 8.0 cm. Dry snow does not seem to have any effect on the impulse radar effectiveness (although it might have a slightly beneficial affect in acting as a matching layer between the air and the ice). Snow thickness is measured by the EM induction, and when snow was taken into account the agreement with surface measurements was good.

5.3.4 Envelope of Applicability

The range of effectiveness of the sensors used is of importance to an operational system. Although the two thickness sensors worked well under the conditions encountered here, it is not clear that they would be able to effectively measure the thickness of all types of ice. As mentioned before, impulse radar is only reliably effective for cold, undeformed, relatively non-saline sea ice. Because it had been used before under other various conditions, it was used here primarily as a comparison sensor for EM induction. Imaging sensors, such as visual, radar or passive microwave, will give an indication of the thickness of very thin ice types as the ice freezes. However, they rapidly become ineffective as the ice grows to more than a few centimeters in thickness.

The EM induction sensor worked remarkably well for an early prototype. The problems encountered were those typically associated with prototype instruments; e.g., equipment calibration, drift, and installation. Once the system was operational and had been thoroughly warmed up, the results over a wide range of ice thicknesses were surprisingly good. Because of the frequencies used, we do not see any fundamental reason why electromagnetic induction would not be a successful ice thickness sensor tool for a wide range of ice thicknesses and types, including those not successfully sounded by impulse radar.

The major limitation to EM induction is likely to be due to its footprint size. Since an area with a diameter approximately equal to the flying height is being sensed, small features will be smoothed out and the estimate of ridge thickness will be under-estimated. In addition, it may be necessary for the inversion routine to take into account the finite conductivity of moist ice that might be encountered, for example, in the spring and summer. This step would not be difficult, but was not evaluated in this experiment. The fact that ice plus snow thickness is measured (rather than ice only) may be important for some applications; for example snow does provide significant friction to icebreaking.

A summary of the effectiveness of various technologies is presented in Figure 18. For very thin ice, several imaging (including visual and SAR) sensors can be effective. However, as the ice becomes thicker, imaging sensors do not give useful thickness estimates and the sounding sensors studied here become effective. For ice that is deformed and/or relatively conductive, impulse radar quickly becomes unable to penetrate effectively. When it is effective the accuracy of the impulse radar is quite high, with a possible error of less than $\pm$ 10 percent, even for ice of an unknown dielectric constant. EM induction, although not accurate for very thin ice, is expected to be effective over a wide range of ice types and thicknesses. As the ice becomes thicker and/or more deformed this sensor is likely to become slowly less accurate but effective for practical measurements over all types of sea ice.

5.3.5 Automated Interpretation

Although beyond the scope of this study, automated interpretation of impulse radar ice sounding data using an expert system has been attempted at the University of Toronto in a joint project with Canpolar [16]. Although the results are preliminary, it appears that this approach could be very effective in making sounding measurements more easily available to non-experts. The work was performed using airborne impulse radar data, but similar approaches may also be useful in improving the availability of real-time interpretation for other technologies.

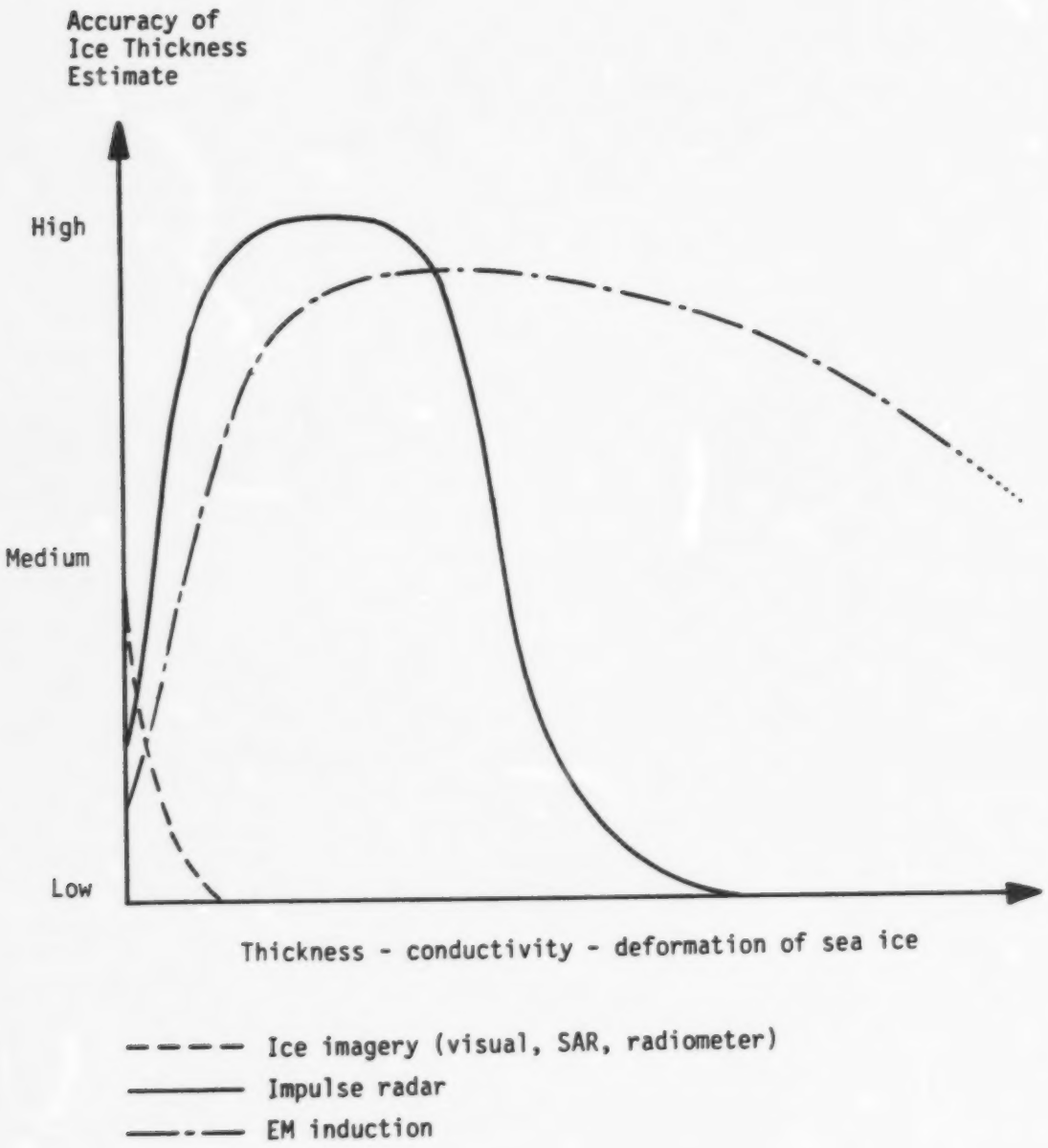


Figure 18. Conceptual sketch showing envelope of utility of various ice thickness sensing technologies.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

As operations in Canada's ice invested waters become more routine, access to effective, real-time information on ice conditions will be critical. The availability of ice imagery from airborne and satellite radars is now becoming an accepted part of ice operations for both strategic and tactical needs. However, none of the imaging sensors provides any significant information on the third dimension -- ice thickness. Because of the importance of this parameter to safety, effectiveness, and cost of marine operations in ice covered waters, it is likely that an ice thickness sensor will become an accepted ice reconnaissance tool.

The results of this study suggest that electromagnetic induction operated from a small helicopter could become a practical ice thickness measurement sensor. Although VHF radar systems can sound cold, undeformed sea ice, they fail totally for warm, saline or deformed ice (such as ridges), and for ice containing water layers or brine inclusions. These conditions are not expected to pose limitations to the effectiveness of EM measurements, although not all these conditions were encountered in our field trials. A field trial of EM induction to sound warm East Coast ice is planned for Spring 1988.

Table 4 gives the target specifications for a helicopter-borne ice thickness measurement sensor set by TDC in 1979, and compares them with the capabilities of the sensors evaluated in our 1987 trials, and with projected capabilities of an airborne EM system after approximately three years of development activity. We conclude that virtually all of the functional requirements (with the exception of total system weight) could be met by this technology.

Moreover, airborne EM is a relatively mature technology which has been used for a number of years for geophysical applications, and more recently for through-ice bathymetry measurements. Canada is a world leader in this technology with several companies (e.g. Geotech, Aerodat, Geonics, etc.) producing or flying helicopter EM systems for world markets. However, the technology has only recently been adopted for ice thickness measurement, and the following items would be required to develop an operational helicopter system:

1. rugged, compact digital electronics and recording system;

2. lightweight, winchable towbird;

3. real-time interpretation software;

4. on-board computer and/or telemetry system.

We believe that the current state of the art is far enough advanced to permit specification and preliminary system design of an operational EM

Table 4. Ice Thickness Sensor Specifications

Parameter	TDC 1979 Target Specs.	1987 Impulse Radar	1987 Airborne EM	1992 Airborne EM ***Projected***
Ice type	Not specified	Cold, undeformed	All?	All
Weather	All	VFR	VFR	< 40 knots wind speed
Ice thickness range	0.3 - 6 m	0.9 - >10 m	0.2? - >10 m	0.1 - >15 m
Accuracy (greater of)	± 10% or ± 10 cm	± 10%* or ± 10 cm	± 10% or ± 50 cm	± 5% or ± 10 cm
Minimum resolvable thickness change	10 cm	10 cm	30 cm	10 cm
Altitude	20 - 300 m	5 - 50 m	20 - 30 m (bird)	10 - 40 m (bird)
Footprint (diameter)	10 m @ 30 m alt.	altitude	bird altitude	bird altitude
Speed	up to 200 knots	up to 75 knots	up to 100 knots	up to 200 knots
Sampling rate	10 m	64/second	10/second	20/second or better
Power @ 28 VDC	20 amps	5 amps	30 amps	20 amps
Weight	25 kg	70 kg	175 kg	125 kg
Calibration	Not required	Not required *except to improve accuracy to ± 5%	Required	Built-in
Interpretation	Not specified	Off-line print-out; manual	Off-line processing; semi-automatic	Real-time automatic
Installation	Not specified	Portable electronics Antenna on hook	Rock-mount electronics Bird on hook	Bolt-no, bolt-off Bird on hook

induction system which could be developed and built in Canada over approximately three years. Therefore, we conclude that Canada could have operational ice thickness measurement systems for its icebreaker fleet which could complement ice imagery by approximately 1992. This system could be designed as an bolt-on, bolt-off instrument for use on standard helicopters and could provide ship masters with real-time ice thickness information for tactical support. This capability is likely to be essential for the operations of Coast Guard ships as they move more routinely into ice invested waters, particularly the Polar-8 icebreaker.

Development of this technology offers a striking opportunity for Canada to solve a particularly Canadian problem by adapting a well developed Canadian technology. In addition to the critical role of improving ice operations, it is likely that once developed this technology could be sold to other countries with similar problems, thereby creating an opportunity for additional export sales and Canadian employment.

6.2 Recommendations

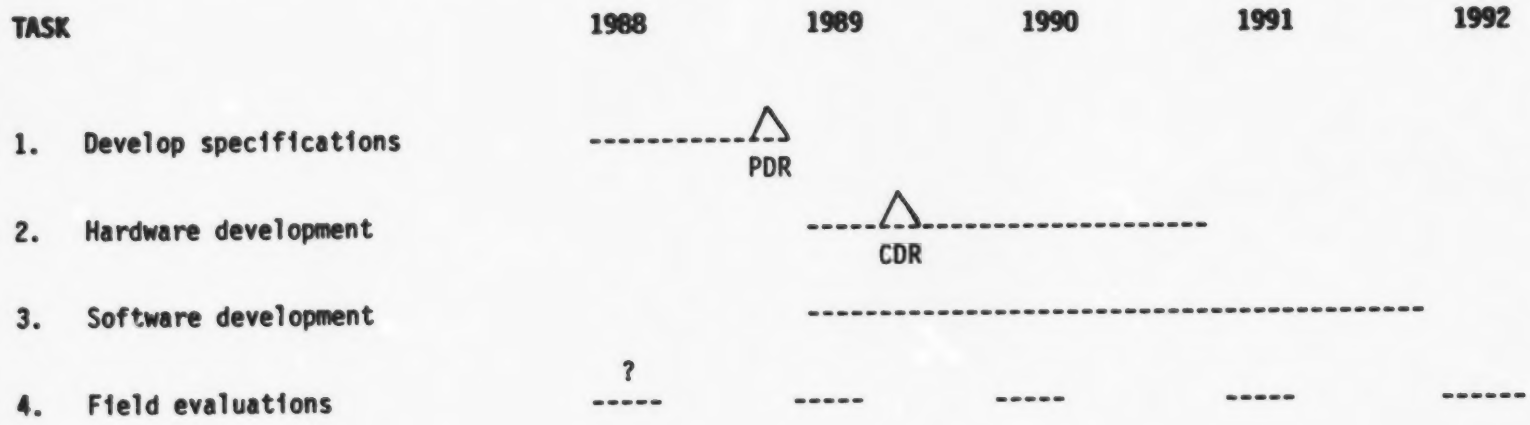
We recommend that Transport Canada undertake development of an operational ice thickness sensor based on electromagnetic induction technology. An approximate development schedule is given in Figure 19 and a summary of development activities and cost is given in Table 5. Cost of development is estimated to be approximately one million dollars over a three to four year period, including allowance for adequate field testing. The development activity could be carried out virtually completely within Canada.

The initial step in this development activity would be to develop comprehensive specifications and a preliminary development plan for the fabrication of an operational prototype. The cost of this study would be approximately $100,000 and take approximately six months. This study would provide a set of specifications which could be used to request bids for fabrication.

We do not recommend further development of radar-based sea ice thickness measurement sensors. As noted above these systems have too many deficiencies to be useful under a wide variety of ice conditions. It is not likely that increased power or receiver design improvements will significantly alter the effectiveness of this technology.

It should be noted that the U.S. Government has also decided to invest in procurement of prototype electromagnetic induction systems for ice thickness measurement. Preliminary trails have already been conducted in Alaska using Canadian technology and it is likely that additional systems will be procured and tested over the next one to two years. However, the results of those studies are largely classified and therefore not generally available to Canadian authorities. Therefore, it is ironic that Canadian capability may fall behind that of the U.S. government, even though the technology originates from Canada.

Figure 19. Development of operational EM ice thickness sensor - Time frame



PDR - Preliminary Design Review

CDR - Critical design Review

March, 1987

Table 5. Development of Operational EM Ice Thickness Measurement Sensor - Tasks and Costs

		Approximate Costs
1.	Develop Specification	$100K
	- examine other ice types (current prototype) - effectiveness in badly deformed ice - minimum configuration required - prepare development plan	
2.	Hardware Development	$400K
	- compact, rugged, digital electronics - internal calibration - optimised bird - winch for bird - pilot subsystem	
3.	Software Development	$200K
	- real-time processing - on-board computer and/or telemetry - algorithms for 2-D structures - internal diagnostics - combine with navigation information	
4.	Field Evaluations	$300K
	- during development stages - at completion of development	
	Total	$1,000K

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Appendix A

Tables summarizing the surface measurements taken along Lines 1, 2 and 3, and snow survey sites in Resolute Passage.

Table A-1

Summary of surface measurements along Line 1.

Site Position on Line 1 (m)	Snow Depth (cm)	Ice Depth (cm)	Salinity Samples	
			Depth (cm)	Salinity
100	10	200	55	1.75
			110	4.25
			190	10.80
200	--	210	---	-----
300	--	220	50	0
			170	4.80
500	14	210	120	1.70
700	--	220	110	3.30
1000	10	210	100	2.90
1100	17	215	110	2.30
1120	39	197	---	----
1140	16	199	---	----
1160	19	190	---	----
1180	45	167	---	----
1200	43	162	---	----
1220	33	192	100	2.50
1240	34	193	---	----
1260	28	210	---	----
1280	23	200	---	----
1300	10	245	100	1.70
1500	30	210	snow	0
			70	0.30
			100	2.30
			140	4.0
1800	27	200	---	----
2000	30	200	---	----
2500	25	165	---	----
3000	39	180	65	4.60
			125	10.50
4500	19	195	---	----

Table A-2

Summary of surface measurements along Line 2.

Site Position on Line 2 (m)	Snow Depth (cm	Ice Depth (cm)	Salinity Samples	
			Depth (cm)	Salinity
0	39	180	65	4.6
			125	10.5
500	29	200	snow	1.0
			40	3.7
			80	4.4
			120	4.8
			160	6.6
700	11	200	84	3.5
			162	11.5
			187	18.2
720	21	215	---	----
740	18 - 26	219	40	2.1
			140	37.2
760	50	195	---	----
780	38	200	44	11.3
			104	7.0
800	12 - 18	211	---	----
820	30 - 35	190	79	7.6
			133	6.1
840	9	205	---	----
860	55	203	56	5.8
			140	4.7
880	23 - 26	202	---	----
900	20	209	62	5.9
			122	5.9
1000	27	212	40	5.8
			80	5.6
			120	6.6
			160	6.7
			170	8.0
2000	10	216	45	9.3
			65	6.2
			93	7.1
			120	10.8
			175	7.7

TABLE A-3

Summary of surface measurements on multi-year floe, along Line 3.

Site # Position on Line 3	Snow Depth (cm)	Ice Depth (cm)	Salinity Samples	
			Depth (cm)	Salinity
1 @ 15m	9	195	65	2.05
			130	3.70
			180	12.20
2 @ 1800m	33	450	65	0.50
			125	1.30
			180	1.30
			240	1.99
			275	2.10
			325	2.20
			375	9.30
3 @ 3800m	67	410	65	0.40
			125	0.30
			190	1.20
			240	1.90
			300	2.30
			360	2.70

Table A - 4

Summary of snow depth measurements taken on April 30, 1987 over first-year ice in Resolute Passage. Courtesy of Dr. Alex Herman of the Bedford Institute of Oceanography.

Position on line (m)	Snow depth (cm)	Position on line(m)	Snow depth (cm)
1	23	26	4.5
2	17	27	4
3	11	28	4
4	7	29	4
5	3.5	30	3.5
6	6	31	3.5
7	4	32	3
8	5.5	33	4
9	3	34	8
10	3	35	8
11	3	36	10
12	3	37	5
13	2	38	7
14	2	39	12
15	3	40	14
16	2	41	14
17	3	42	15
18	4	43	16
19	4	44	21
20	4	45	25
21	4	46	28
22	3.5	47	22
23	4.5	48	14
24	8	49	8
25	6	50	5.6

Position on line (m)	Snow depth (cm)	Position on line(m)	Snow depth (cm)
51	25	76	17
52	3	77	12
53	35	78	18
54	3	79	13
55	3	80	14
56	2	81	14
57	2	82	17
58	3	83	19
59	2	84	20
60	3	85	11
61	4	86	9.5
62	4	87	5
63	12	88	3
64	7	89	3.5
65	7	90	4
66	10	91	4
67	15	92	4
68	14	93	4.5
69	17	94	6
70	18	95	7
71	21	96	14
72	21	97	23
73	18	98	20
74	25	99	21
75	20	100	20

Position on line (m)	Snow depth (cm)	Position on line (m)	Snow depth (cm)
101	11	126	8
102	10	127	10
103	8.5	128	6.5
104	7	129	4
105	11	130	6
106	5	131	9
107	2	132	10
108	2	133	12
109	3	134	12
110	3	135	14
111	2.5	136	14.5
112	3	137	9
113	3	138	9
114	7	139	4
115	4	140	5
116	8.5	141	6
117	7	142	6
118	4	143	5
119	4	144	6
120	3	145	6
121	3.5	146	5.5
122	4	147	5.5
123	9	148	4.5
124	10	149	3.5
125	8	150	9

Position on line (m)	Snow depth (cm)	Position on line (m)	Snow depth (cm)
151	12	176	15
152	11.5	177	14
153	9	178	16
154	8	179	18
155	7	180	14
156	4.5	181	13.5
157	4	182	4
158	5	183	11.5
159	6	184	4
160	8	185	12
161	7	186	9
162	9	187	11
163	10	188	11
164	11.5	189	16
165	15	190	12.5
166	15	191	19
167	15	192	22
168	15	193	25
169	15	194	36
170	15	195	38
171	15	196	36
172	15	197	40
173	14	198	45
174	14	199	40
175	13	200	36